Oman Fisheries & Aquaculture

Climate Change Risk Assessment

Technical Report

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Executive Summary

Fish and seafood are a global commodity with an estimated global first sale value of over US$ 390 billion per year, this figure is increased by value-added processing as fish products pass through the supply chain. Fish are also an important part of global food supplies; 3.3 billion people rely on fish for over 20% of their annual animal protein intake.

As well as being of global significance, fisheries are an important source of revenue, employment and food in Oman. Fisheries in Oman generated a first sale price of almost US$ 400 million in 2019 including over US$ 260 million of exports. This is a contribution of approximately 0.8% of national GDP and provided over 50,000 direct jobs.

Fisheries are recognised as one of the five sectors of Oman's economy that can drive economic diversification, and ambitious investment plans amounting to US$ 2.5 billion have been proposed to rapidly develop Oman's wild fisheries, aquaculture and processing sectors.

Wild fisheries and aquaculture are directly, or indirectly, connected with the natural environment and exposed to the effects of climate change. Climate driven changes in productivity and sustainability can directly impact the wild fisheries and aquaculture sectors and ripple through supply chains, impacting associated investments, infrastructure and downstream processing.

Therefore, implementing actions to build resilience and adaptive capacity in fisheries and aquaculture is necessary to futureproof the livelihoods, food security, revenues and investments associated this sector.

Through the United Nations Framework Convention on Climate Change (UNFCCC), Oman has agreed to take ambitious actions to adapt to the effects of climate change, and a decline in fisheries productivity has been identified in Oman's Nationally Determined Contribution as a priority for adaptation action.

The Intergovernmental Panel on Climate Change (IPCC) has established a framework for conducting climate change risk assessments to understand how the different components of climate risk affect linked ecological-economic systems.

The results of the fisheries and aquaculture climate change risk assessment presented in this report facilitate the development of prioritised resilience and adaptation building actions to ensure long-term environmental and economic sustainability in the fisheries sector in Oman.

The fisheries climate risk assessment took account of ecological sensitivity and exposure to climate change impacts, as well as the level of climate hazard fisheries are exposed to and the socioeconomic vulnerability adaptive capacity of difference components of the fishery.

The four coastal wilayats identified as being most at risk from climate change impacts on fisheries are Ja'alan Banī Bū Hassan, Salālah, Mutrah and Al-Jāzer.

Ja'alan Banī Bū Hassan is most exposed to climate risk due to the high socio-economic vulnerability, the limited diversity of species caught and high exposure to increasing temperature and cyclone risk.

Salālah is at increased risk due to high species sensitivity and low diversity of catches, Mutrah has high risk due to species sensitivity and exposure to climate hazards, and Al-Jāzer was identified as being at increased risk due to low species diversity, moderate species sensitivity and exposure to climate impacts.

The dhow hand line, troll line and fish trap fisheries in Batinah and Muscat Governorates are identified as most at risk due to high values for all components of the risk assessment – socio-economic vulnerability, sensitivity of the target species, limited diversity in catches and high exposure to climate hazards.

The industrial and coastal fishery are the most capital-intensive fleets and show strong socio-economic resilience to climate change, and low risk overall.

The aquaculture climate risk assessment took account of species' thermal sensitivity, exposure to sea level rise and storm surge, hazard of low oxygen exposure and disease vulnerability. Due to the early stage of development of aquaculture in Oman, the risk assessment was based on future projections of aquaculture production.

Shrimp aquaculture is identified as most at risk due to vulnerability of shrimp ponds to flooding and storm surges and due disease exposure, even though whiteleg shrimp have low thermal sensitivity to the direct temperature impacts of climate change. Flood and storm surge risk will vary between sites depending on the exact setting of each shrimp farm.

Gilthead bream, which is already being farmed in Muscat Governorate, also has a moderately high overall risk score. This is due to high scores for thermal sensitivity and exposure to low oxygen hazard.

This analysis does not provide a quantitative estimate of the potential impacts of climate change on fisheries and aquaculture; however, it identifies priority climate change associated risk factors for different sectors of the Oman's fisheries and aquaculture sector.

Climate change is happening; implementing targeted adaptation and resilience building measures is necessary to protect the food production, livelihoods, investments and supply chains that are dependent on productive fisheries and aquaculture.

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1 Introduction

The ocean provides human societies with a wide variety of goods and services, ranging from food and employment to climate regulation and cultural nourishment (Hassan et al. 2005). Climate change is already shifting the abundance, distribution, productivity and phenology of living marine resources (Poloczanska et al 2013, Phillips & Pérez-Ramírez 2018, FAO 2018) and, thereby impacting many of the ecosystem services on which humans depend (IPCC 2019). These impacts, however, are not being experienced uniformly around the world or across countries but depend on the characteristics and context of the community or business affected. Raising awareness and understanding the risk to human systems is, therefore, a key first step (Allison et al. 2009) to developing and prioritising appropriate adaptation options in response to the challenges of the climate crisis (Johnson et al. 2016).

The Sultanate of Oman has a long coastline (3,165 km). The main economic activity of many coastal communities is fishing, which provides an important source of income, but also a supply of fish protein to local communities, urban areas and the export markets. Oman is one of the largest fish producers in the region and a net exporter of fish and fish products.

The fisheries sector in Oman, which includes wild-capture, aquaculture and on-shore processing, has been identified within the Omani Tanfeedh national economic programme as one of five sectors that can drive economic diversification. Oman is much more reliant on fisheries than other Gulf States. Fisheries generated OMR 306 million in 2019 including over OMR 100 million of exports. This is a contribution of approximately ~0.8% of national GDP. Investment to the fishing sector of OMR 1 billion are planned under the Tanfeedh national economic programme, growing the annual GDP contribution to OMR 800 million and creating 8,000 jobs.

However, a global analysis by Cheung et al. (2018) on the future of fisheries productivity worldwide under climate change, indicated that Oman - out of 196 countries and overseas territories examined – is particularly vulnerable, with models suggesting that the fisheries catch could decline by as much as 24.8% under a high-carbon emission scenario (RCP8.5) during the twenty first Century. This highlights the importance of building resilience and adaptive capacity in the fisheries sector.

With global capture fisheries either having reached peak levels or predicted to decline in decades to come, aquaculture is of rising importance to ensure food security. In Oman, the aquaculture sector has developed relatively recently compared to more 'traditional' aquaculture countries such as Norway and Chile; nevertheless, annual production has grown rapidly since its inception in the 1990s, from 13 t produced in 1998 to over 450 tonnes in 2018 (FAO, 2018). While the aquaculture sector in Oman may still be regarded as being in its early stages of development, Oman aspires to grow the industry rapidly. This is not only to generate revenue and enhance food security, but also to create a skilled workforce of Omani nationals work in the aquaculture industry. However as is the case with the fisheries sector, climate change is also impacting the aquaculture sector worldwide (review: Callaway et al. 2012). Predicted impacts from climate change in the region might make aspirations to expand and diversify a profitable aquaculture sector, more challenging to achieve in the long term.

This project will provide: (1) a first climate change risk assessment for fisheries and aquaculture in Oman and (2) associated recommendations for actions to support adaptation and build resilience to these risks. This report presents the initial climate change risk assessment.

2 Climate Vulnerability Assessments (CVAs)

In 2001, the Intergovernmental Panel on Climate Change (IPCC) developed a framework to assist agencies in understanding the facets that interact to determine climate change vulnerability in both natural and socio-economic systems. 'Vulnerability' (V) is viewed as being a function of 'exposure' (E) of the particular system to climatic hazards, 'sensitivity' (S) of the system to changes in climate, and 'adaptive capacity' (AC), i.e. the degree to which adjustments in practices, processes, or structures can modulate or offset the potential for damage (IPCC 2001) (Figure 1).

A number of climate vulnerability assessments (CVAs) have since been directed towards understanding impacts in the fisheries and aquaculture sectors specifically. At the global scale, Allison et al. (2009) performed a CVA of 132 national economies to potential changes in capture fisheries as a result of climate change and concluded that many of the world's most vulnerable countries are also among the world's poorest. This vulnerability was due to the combined effect of predicted warming, the relative importance of fisheries to national economies and diets, and limited societal capacity to adapt to potential impacts and opportunities. In the analysis conducted by Allison et al. (2009), Oman was not included in the scoring exercise as the authors could not find sufficient data. However, Basiak et al. (2017) provided an update and calculated a vulnerability index of 147 countries (including Oman) by drawing on the most recent data related to the impacts of climate change on marine fisheries. Seven out of the ten most vulnerable countries according to the resulting index were Small Island Developing States, and the top quartile of the index included countries located in Africa (17), Asia (7), North America the Caribbean (4) and Oceania (8). More than 87% of least developed countries were found within the top half of the vulnerability ranking, while the bottom half included all but one of the Organization for Economic Co-operation and Development member states (i.e. the richest countries). The Sultanate of Oman was ranked 74th out of 147 countries in terms of vulnerability, with a score of 0.49 (from a range spanning 0 to 1).

Some of the earliest sub-national CVAs were conducted in India and southeast Asia. For instance, Adger (1999) conducted a CVA of coastal communities in northern Vietnam to extreme events. In that work, vulnerability was defined as the "exposure of individuals or collective groups to livelihood stress as a result of the impacts of such environmental change". In a later example, O'Brien et al. (2004) produced maps of vulnerability to the multiple pressures caused by climate change. Cinner et al. (2013) carried out a joint ecological and socio-economic CVA of ten coastal communities in Kenya, Colburn et al. (2016) carried out a similar assessment for fishing communities in the United States and Pinnegar et al. (2018) carried out a CVA to determine how each of the Caribbean Island of Dominica's ten parishes differed in terms of fisheries vulnerability (to catastrophic hurricanes and long-term climate change).

Barsley et al. (2013) provided a general overview of CVA work focused on fisheries and aquaculture worldwide. “Best practice” guidelines to the application of vulnerability assessments for fisheries and aquaculture have now been developed by the UN Food and Agriculture Organisation (FAO, 2015; Johnson et al., 2016).

Vulnerability = f(exposure, sensitivity, adaptive capacity)

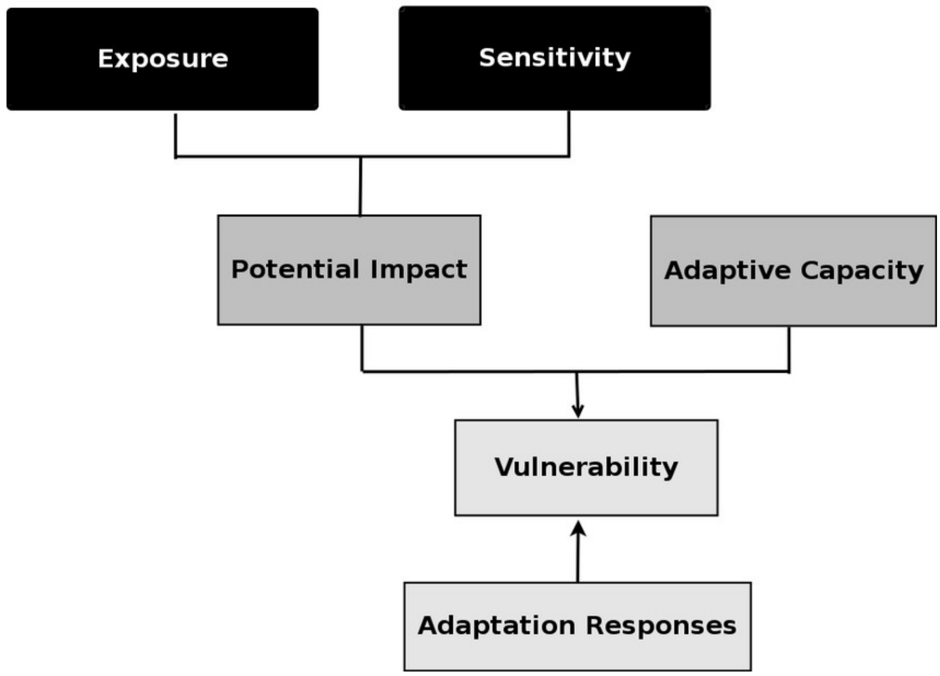


Figure 1: The basic IPCC Climate Change Vulnerability Assessment (CVA) framework.

Within Oman, a number of climate vulnerability analyses (CVAs) have been performed, but not in the context of fisheries and aquaculture. Hereher et al. (2020) provided an assessment of coastal vulnerability to sea level rise throughout Oman and showed that highly vulnerable coastal regions account for 805 km of the coast, mostly along Al-Batinah plain in the north and along some scattered sectors at the eastern coast of the country. Moderate vulnerability coasts total 695 km mostly at the headlands along the Arabian Sea, whereas the low vulnerability coasts include the remaining shores along Musandam Peninsula and the eastern coast. The northernmost governorate of Oman (Musandam) was included in the fisheries vulnerability assessment carried out by Wabnitz et al. (2018) for countries in the Arabian Gulf region. Results from the vulnerability assessment integrating changes in fishery catch potential with socioeconomic indicators identified Bahrain and Iran as most vulnerable to the impacts of climate change on fisheries. Oman, the UAE and Iraq were characterised as being of medium vulnerability, while Kuwait and Saudi Arabia exhibited the lowest vulnerability in the region.

In recent years, the approach to CVA's developed by the Intergovernmental Panel on Climate Change (IPCC) has shifted from a focus on "vulnerability" to a focus on "risk" (Oppenheimer et al. 2014), in part due to criticisms of the negative framing that "vulnerability" implies (Connelly, et al. 2018). This new framework (figure 2) was first presented in 2012 in the IPCC Special Report on Extreme Events (SREX) (Cardona et al., 2012; Lavell et al., 2012), but the more 'traditional' approach to defining vulnerability continues to predominate. A 'risk' based approach, built around the more recent IPCC framework has been adopted under the European Union H2020 project 'CERES' (Climate change and European aquatic RESources) to determine relative levels of risk to EU fishing fleets and coastal communities as a result of climate change. In this study a trait-based approach was combined with ecological niche models to differentiate climate hazards between populations of fish. These outputs were then used to assess the relative climate risk for 380 fishing fleets and 105 coastal regions in Europe. Countries in southeast Europe and the UK had the highest relative risks to both their fishing fleets and their fishery-dependent coastal communities while, in other countries, the risk-profile was greatest at either the fleet or community level (https://doi.org/10.1101/2020.08.03.234401).

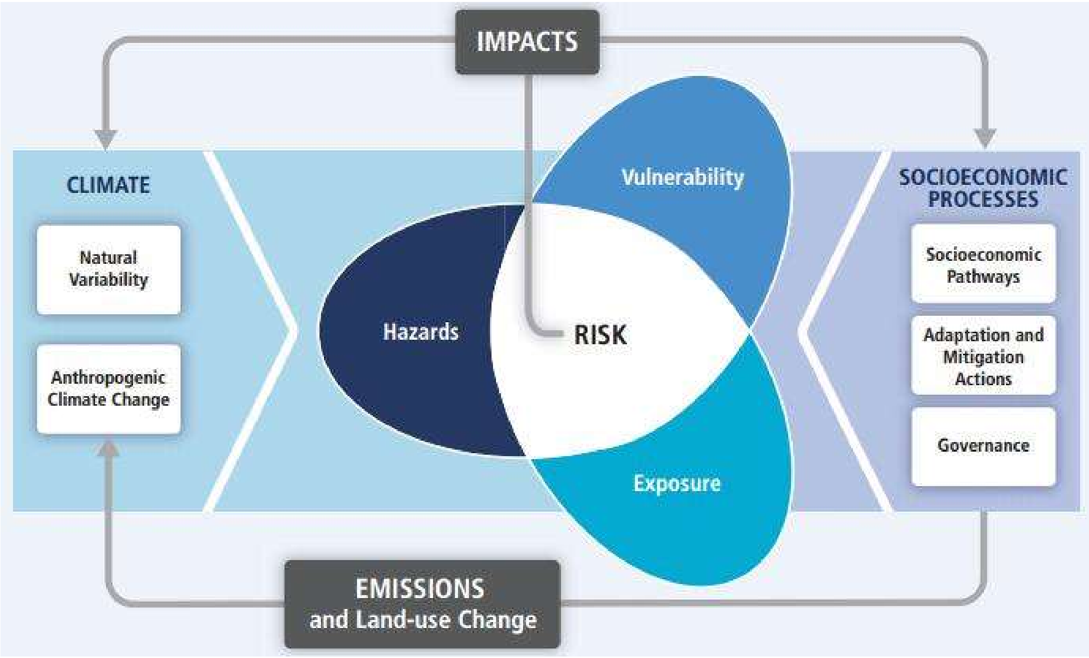


Figure 2: Illustration of the fundamental concept of risk and vulnerability to climate change. Source: IPCC 2014 (Fifth Assessment Report, Working Group 2, Chapter 19, Figure 19-1).

In the present study for the Sultanate of Oman, we have used a hybrid approach taking our inspiration from the recent analysis of European fisheries (see above). However, the approach has adapted to apply the method for assessing species sensitivity based on the approach taken by Pinnegar et al. (2018).

3 Climate Change and the marine environment in Oman

In the Sea of Oman, minimum winter Sea Surface Temperatures (SSTs) of around 22°C occurs in February, and a maximum of 32°C in August, with water along the Arabian coast (including around the Musandam Peninsula of Oman) being generally warmer than along the Iranian coast (UNEP, 1994; ROPME, 2013). Moving from the Sea of Oman to the Oman coast of the Arabian Sea (northern Indian Ocean), the temperature regime becomes increasingly influenced by the Indian monsoon. During the winter monsoon period, SST reduces from 26°C in November to 22–23°C in February (see figure 7). By contrast, with the onset of the summer monsoon, the temperature rises to ~28°C in May until upwelling dominates and temperatures in the upwelled areas drop below 22°C near the coast in August. The lower temperatures near the coast of Dhofar persist until the upwelling weakens in November (ROPME, 2013).

A key finding of the IPCC 5th Assessment Report (AR5) was that between 1950 and 2009, annual average SST in the Arabian Gulf increased by 0.59°C (Piontkovski and Claerebout, 2012; Hoegh-Guldberg *et al.,* 2014). More localised studies have become available, for example Noori *et al* (2019) modelled past and future trends in SST in the Arabian Gulf and Sea of Oman and found an increase in the mean, minimum, and maximum trends of daily SST anomalies between 1982 and 2015, corresponding to approximately 1˚C over 34 years. An analysis of SST in the Arabian Gulf by Shirvani *et al*. (2015) indicates that SST increased abruptly during the period 1990-2010.

Temperature data compiled following occasional expeditions on the Omani Shelf suggest an increase in temperature of 1.2°C over the past 50 years in the upper 30 m layer of seawater of the Arabian Sea during the south-west (summer) monsoon (Piontkovski and Al-Oufi, 2015). However, long-term measurements of SST from across the region are sorely needed in order to discern statistically significant increases that might be attributed to climate change.

The IPCC model projection for the region (Hoegh-Guldberg *et al.,* 2014) revealed that under RCP8.5, by 2099, SST could increase by 2.8–4.26°C in the Arabian Gulf and by approximately 2.5°C in the Sea of Oman and Arabian Sea, relative to data of 2005 (see figure 3). The higher SSTs in the Arabian Gulf are principally due to the shallow depth that allows a rapid transfer of heat across the water column as well as the limited flush rate through the Strait of Hormuz (Reynolds, 1993; UNEP, 1994; Sadrinasab and Jochen, 2004). An increase in the incidence of marine heatwaves is projected as a consequence of this elevated warming trend (Hoegh-Guldberg *et al.,* 2014) and will have signifcant consequences for ecosystems in the region (Fordyce *et al*., 2019).

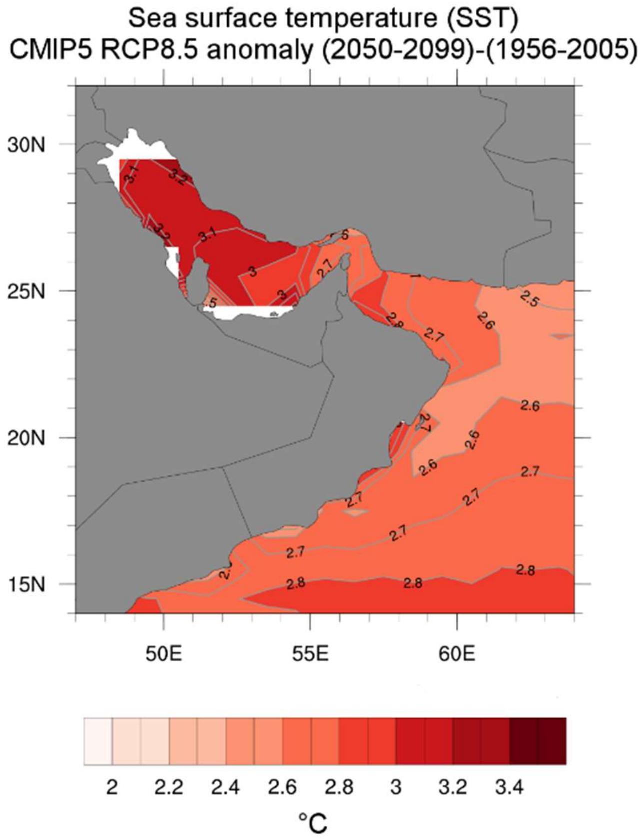


Figure 3: The projected difference in the annual average sea surface temperature (SST) in 2050–2099 under RCP8.5 compared to the historical reference period (1956–2005), calculated using CMIP5 models. White shading denotes areas where data are missing ESRL : PSD : Climate Change Web Portal _ Maps MM" 2018. From AGEDI (2016a).

Due to the solubility effect, warmer waters contain less dissolved oxygen compared to cooler waters (Carpenter, 1966) and lead to increases in the respiration rates of marine organisms (Pauly and Kinne, 2010). Increased stratification, as a result of SST warming, adversely affects the oxygenation of deeper water masses, which also leads to a decrease in dissolved oxygen concentration, particularly near the seabed (Vaquer-Sunyer and Duarte, 2011). Oxygen minimum zones (OMZs) generally refer to specific regions with midwater concentrations below 2 mg/L (hypoxia) caused by vertical stratification due to temperature differences and respiratory drawdown of oxygen. More than 50% of the total area of OMZs in the world's oceans occur in the northern Indian Ocean (Helly and Levin, 2004; Stramma *et al.,* 2010). The OMZ that occurs in the Sea of Oman and Arabian Sea is the most intense in the world, with near-total oxygen depletion at depths from 200 to 1000 m (Piontkovski and Al-Oufi, 2015). Regions with low dissolved oxygen concentrations are expected to increase in frequency and extent over the coming century, partly in response to climate change (Hoegh-Guldberg *et al.,* 2014), with the Arabian Sea and Sea of Oman projected to undergo stronger deoxygenation than the wider Indian Ocean (Stramma, 2010; Bopp *et al*., 2013; Long *et al*., 2016).

On average, one to two tropical cyclones form over the northern Indian Ocean each year, with only a few of these being intense enough to be classified as "severe" (ROPME, 2013). There is marked seasonal variation, with two annual peaks in tropical cyclone genesis in months preceding and following the monsoon (April to May and October to December, respectively; Murakami *et al*., 2013). From 1979 to 2008, a total of 41 cyclonic storms formed in the northern Indian Ocean, of which 23 made landfall (usually over Oman). Over the period 1979 to 2008, there was an average of 4.7 cyclonic storm days over the Arabian Sea each year (ROPME, 2013).

Cyclone Gonu (Rafiq *et al*., 2015), which became the strongest storm to make landfall in Oman to date, caused an estimated 4 billion USD in damages and 100 deaths across Oman, UAE, and Iran (ROPME, 2013). Cyclone Gonu also led to severe degradation of many coastal habitats including coral reefs as a result of wave impact (Foster *et al*., 2011; Bento *et al*., 2016). Similarly, in May 2010, record heat over southern Asia helped elevate sea temperatures in the northern Indian Ocean to 2°C above normal and contributed to the formation of Tropical Cyclone Phet, the second strongest tropical cyclone ever recorded in the region (Haggag and Badry, 2012). Cyclone Phet peaked as a Very Severe category storm, killing 44 people and causing 700 million USD in damage to Oman. Tropical cyclone Mekunu, on 21st May 2018, was the strongest storm to strike the Dhofar Governorate since 1959. Mekunu caused landslides and flooding, 20 fatalities and about 1.5 billion USD in damage.

Publications on the future frequency and magnitude of tropical cyclones in a warming climate suggest that the strongest storms could increase in intensity of 2–11% by 2100, but the total number of storms would fall globally by 6–34%, (Knutson *et al.,* 2010). A modelling study under a high emissions scenario (based on CMIP3 modelling under the Special Report on Emission Scenarios (SRES) A1B scenario) suggested that the overall number of tropical cyclones generated at the basin scale in the Indian Ocean basin would not change significantly, but, a shift in the location of storms could lead to a significant increase in the number of tropical cyclones occurring in the Arabian Sea by the end of this century (Figure ; Murakami *et al.,* 2013).

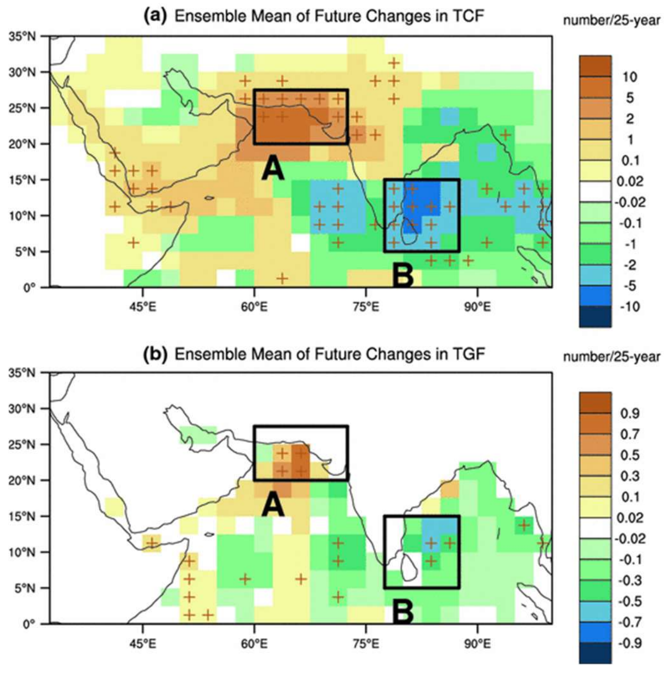


Figure 4: Average model projections of future changes in a) tropical cyclone frequency (TCF) [number/ 25 years] and b) tropical cyclone genesis frequency by the end of century. The plus symbols indicate that the differences are statistically significant (Murakami et al., 2013). 'A' is the Arabian Sea, 'B' is the southern Bay of Bengal.

4 Introduction to the fisheries and aquaculture in Oman

Fisheries and agriculture are among the oldest and most important production sectors in the Omani economy. They play a vital part in feeding the population, providing employment for large numbers of Omanis and helping to boost the country's GDP. A total 25,030 fishing vessels were reported in 2019, of which over 96 percent were less than 12 m in length. The fishery sector provided about 50,405 direct jobs in 2019. In 2019, exports and re-exports of fish and fishery products amounted to 207,856 tonnes, while imports amounted to 35,072 tonnes. The average annual per capita seafood consumption in Oman was about 55.7 kg in 2019 having risen rapidly, from only 23.9 kg in 2013 (FSD 2019).

According to government statistics, total capture production was stable between 2005 and 2011 at around 155,000 tonnes per year but in 2012 started growing significantly and by 2019 reached 579,187 tonnes. This growth was primarily due to small pelagic and tuna species (FSD 2019). Since 2012, small pelagic fish have made up the bulk of the fishery landings. In 2019, these species represented 60.3% percent (349,474 tonnes) of total landings, with the majority made up of sardines (78.7%), followed by horse mackerel (5.7%), small jacks (5.5%), anchovy (5.0%) and Indian mackerel (3.2%) across the artisanal, coastal and industrial fleet segments (FSD 2019). Large pelagic species came in second and represented 20.0 percent (115,578 tonnes) of the total catch. The most important species fished were the yellowfin tunas (32.1%%), large jacks (13.1%), longtail tuna (12.7%), and barracudas (9.4%) (FSD 2019). Demersal catch occupied the third position in 2019 (around 15.2%, 88135 tonnes) and consisted of a diverse range of species including emperors (19.3%), ribbonfish (17.3%), croaker (10.2%), Rabbitfish (9.3%), seabreams (8.9%) and catfish (8.4%). Sharks and rays came in fourth followed by crustaceans, i.e. lobsters, shrimp and molluscs (abalone and cuttlefish) (FSD 2019).

Artisanal fisheries remain the most important sub-sector of the fishing industry in Oman and represented 95.8% by weight and 94.7% by value (OMR 288 Million) in 2019. In 2019, the most important landing sites for the artisanal fleet were along the Arabian Sea (403,411 tonnes, 72.7%) followed by the Sea of Oman with a production of 125,782 tonnes (22.7%) followed by the Arabian Gulf (Musandam Governorate) where a production of only 25,993 tonnes (4.7%) was registered (FSD 2019). Within the artisanal fishery sector, the Al Wusta Governorate is the most important region with landings representing approximately 37.2% (206,697 tonnes) in 2019. The next district in terms of importance is the South Sharqiyah Governorate with artisanal landings representing 26.0% (144,458 tonnes) of the total catch in 2017. The Dhofar Governorate ranks third with artisanal productions around 13.4% (74,383 tonnes) in 2019 (FSD 2019).

The Arabian Gulf has a tropical climate. Extensive tidal shallows (from 0 to 50 m), which are characteristic of most of the coast of the Musandam Peninsula, are ideal for trap fishing. Fishermen at the mouths of the "wadis" (rivers) benefit from rich stocks nourished by the deepwater upwelling. Here, beach seine netting (called "yaroof") and the casting of drift nets ("al-hayali") or the use of gillnets ("al-liekh") often set on the bottom, are also deployed, usually from dhows. Long-lines (known locally as "manshalla") are also used. In recent years there has been substantial investment in the fishing fleet with an increase in boat numbers, boat sizes and better equipment. The species targets are tuna (*Thunnus tonggol*, *Auxis thazard*, *Thunnus albacares*), grouper (*Epinephelus tauvina*, *Epinephelus chlorostigma*, *Epinephelus areolatus*), silver grunt (*Pomadasys argenteus*), spangled emperor (*Lethrinus nebulosus*), soldierbream (*Argyrops filamentosus*), blackspot snapper (*Lutjanus ehrenbergii*), narrow-barred Spanish mackerel (*Scomberomorus commerson*), great barracuda (*Sphyraena barracuda*), longfin trevally (*Carangoides armatus*), Indian threadfish (*Alectis indicus*), Indian mackerel (*Rastrelliger kanagurta*), greater amberjack (*Seriola dumerilii*), anchovies (Engraulidae), herrings, sardines (Clupeidae).

The Sea of Oman is 200 miles (320 km) wide and situated between Ra's Al-Ḥadd in Oman and Gwādar Bay on the Pakistan/Iran border. It is 350 miles (560 km) long and connects with the Arabian Gulf to the northwest through the Strait of Hormuz. The fishing practised is mainly artisanal and is active year-round. Important fisheries exist for demersal, benthic and pelagic species. The primary species targeted include: Emperors (Lethrinidae), groupers (*Epinephelus tauvina*, *Epinephelus chlorostigma*, *Epinephelus areolatus*), tigerperches (Terapontidae), goatfishes (Mullidae) porgies, seabreams (Sparidae), sharptooth jobfish (*Pristipomoides typus*), tuna (*Thunnus tonggol*, *Thunnus albacares*, *Auxis thazard*), sharks (Sphyrnidae), barracudas (Sphyraenidae), kawakawa (*Euthynnus affinis*), sharptooth jobfish (*Pristipomoides typus*), narrow-barred Spanish mackerel (*Scomberomorus commerson*), Marlins, sailfishes, (Istiophoridae), seabasses (Serranidae), porgies, Carangids (Carangidae), requiem sharks (Carcharhinidae), sharks (Sphyrnidae), Indo-Pacific sailfish (*Istiophorus platypterus*), striped bonito (*Sarda orientalis*), talang queenfish (*Scomberoides commersonnianus*), anchovies (Engraulidae), herrings, sardines (Clupeidae), Indian mackerel (*Rastrelliger kanagurta*), redtail scad (*Decapterus kurroides*), dolphinfishes (Coryphaenidae), blacktip trevally (*Caranx heberi*), striped bonito (*Sarda orientalis*), sand devils (Squatinidae), and black pomfret (*Parastromateus niger*).

There is approximately 1200 km of Omani coast along the Arabian Sea (northern Indian Ocean), extending from Ra's Al-Hadd in the northeast to the Oman/Yemen border in the southwest. In 2019, the Arabian Sea was responsible for 72.6 percent of the total fish catch (but only 56.8% of total value) and employed around 26,879 fishermen (53.3% of the total fishermen in Oman) operating 14,085 boats (56.3% of the national fishing fleet) (FSD 2019). The major fishing gear used are artisanal gillnets, trawls, long-lines and purse seines. The skiff cuttlefish and squid fishery has been using barriers, fences, weirs, corrals, etc. This fishery operates seasonally from September to October and the target species are the pharaoh cuttlefish, Sepiidae loliginidae (inshore squid) and Octopodidae (octopuses). The skiff net fishery is an artisanal fishery practised year round using gillnets and entangling nets; the resources exploited are pelagic stocks and the target species are sardines (Clupeidae), sea catfishes (Ariidae), herrings, Indian mackerel (*Rastrelliger kanagurta*), chub mackerel (*Scomber japonicus*), largehead hairtail (*Trichiurus lepturus*), mullets (Mugilidae), talang queenfish (*Scomberoides commersonnianus*), hammerhead sharks (Sphyrnidae), and requiem sharks (Carcharhinidae). The skiff shrimp fishery practised in the Arabian Sea is artisanal and operates from September to December. The species fished are the green tiger prawn (*Penaeus semisulcatus*) and the Indian white prawn (*Penaeus indicus*). The dhow net fishery is an artisanal activity practised all year using gillnets and entangling nets. The species aimed for are tuna (*Thunnus tonggol*, *Thunnus albacares*), talang queenfish (*Scomberoides commersonnianus*), mackerel (*Scomber japonicus*, *Scomberomorus commerson*), bluefish (*Pomatomus saltatrix*), kawakawa (*Euthynnus affinis*), black marlin (*Makaira indica*), sailfishes (Istiophoridae), barracudas (Sphyraenidae), giant trevally (*Caranx ignobilis*) and a variety of carangids (Carangidae). The dhow fish trap fishery is practised all year using barriers, fences, weirs, corrals, etc. as fishing gear. The demersal stocks are the exploited resources and the target species are mainly groupers, seabasses (Serranidae), porgies, seabreams (Sparidae), snappers, jobfishes (Lutjanidae) and emperors (Haemulidae, Lethrinidae).

The main species targeted by the Oman industrial long-line fishery is the yellowfin tuna (*Thunnus albacares*) fished all year round by steel vessel longliners equipped with handling and processing equipment allowing sorting, packing, quick freezing and fish storing onboard. The vessels are manned by a team of 20 persons that stay on board for trips lasting up to 35 days. The port of Mutrah (Muscat Governorate) is the final destination of this kind of fishing.

Scientific surveys from the last four decades have recorded stocks of horse mackerel (*Trachurus indicus*) in excess of 1 million tonnes in Oman's Arabian Sea coastal waters (e.g. Strømme 1986). A new fishing company (Al Wusta Fisheries Industries LLC) has been established with the aim to develop pelagic fishing in Oman's Exclusive Economic Zone and the Indian Ocean using state of the art fishing vessels and processing facilities. The FV Victoria is a 93 m pelagic freezer trawler, operating from Salalah, Oman with an exclusive fishing license for horse mackerel. Official landings data for this industrial 'fleet' first appear in government statistics for 2018.

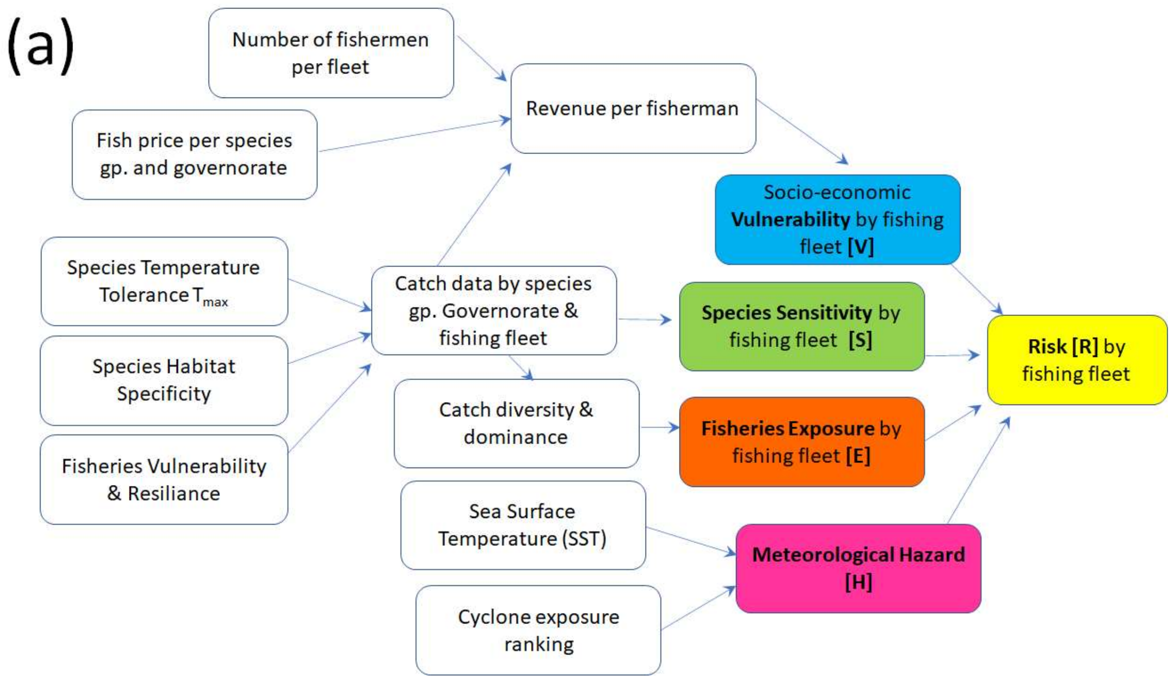
The production of aquaculture products in Oman was only 77 tonnes in 2017 (FSD 2019). However, there is a strong commitment from the government to develop this sector in a competitive and sustainable manner that is in harmony with the social, economic, cultural and historic values of the country. The first commercial aquaculture operation in Oman was a fish cage operation located in the Muscat Governorate which started production in 2003. The Musandam Peninsula in the northern tip of the country is characterized by deep fjord-like inlets which are suitable for marine cage culture, though the presence of occasional algal blooms is an issue.

Recent statistics released by Oman's Ministry of Agriculture and Fisheries (FSD 2019) revealed that the Sultanate's aquaculture production rose by 133 per cent in 2019 compared to 2018, to reach 1,054 tonnes with a total value of OMR 2 million. In 2019 production was limited to sea bream (*Sparus aurata*) and tilapia (*Oreochromis niloticus*) – the former accounting for 862 tonnes and the latter for 192 tonnes. However, projects for species including shrimp (*Penaeus monodon, Penaeus indicus* and *Penaeus vannamei*), abalone (*Haliotis mariae*), cobia (*Rachycentron canadum*), silvery black or sobaity seabream (*Sparidentex hasta* = *Acanthopagrus cuvieri*) and seaweeds are currently planned or under development. Moreover, there is interest to produce high-value species such as groupers (*Cephalopholis hemistiktos* and *Epinephelus tauvina*), as well as amberjacks (*Seriola quinqueradiata, S. dumerili* and *S. lalandi*).

The aims of the present Climate Risk Assessment (CRA) for fisheries and aquaculture in Oman are: (1) to identify the commercial fisheries and aquaculture species in Oman that are the most sensitive to long-term climate change; (2) examine the relative 'exposure' of different fishing fleets and wilayats in Oman to climate impacts on fisheries; (3) consider the vulnerability of different communities in Oman to climatic shocks, based on their economic dependency or adaptive capacity etc., that are in-turn based upon indices of social inequality, poverty, housing quality etc., (4) assess the 'hazard' posed by temperature rise or exposure to cyclones, and (5) determine the overall risk profile for fishing fleets, aquaculture facilities and coastal wilayats in Oman.

5 Fisheries Assessment - Methods

We have applied an integrated approach to climate risk assessment (CRA) across the entire Oman fisheries sector. The CRA has four major components (Figure 5). The first and most fundamental of these is the species 'sensitivity' component, where the sensitivity associated with climate-change impacts on individual species is quantified. We then use these metrics as inputs into two parallel climate-risk assessments focussing on coastal regions (wilayats) and fishing fleets (combinations of Governorate and fishing gear). In each of these cases, the weighted sensitivity scores were integrated at the region or fleet level, based on official landing statistics, to form the region- or fleet-specific sensitivity score [S]. These sensitivity data are then complemented with region- and fleet-focused, hazard [H] exposure [E] and vulnerability [V] metrics to produce an overall climate-risk [R] for each section of the fishery.



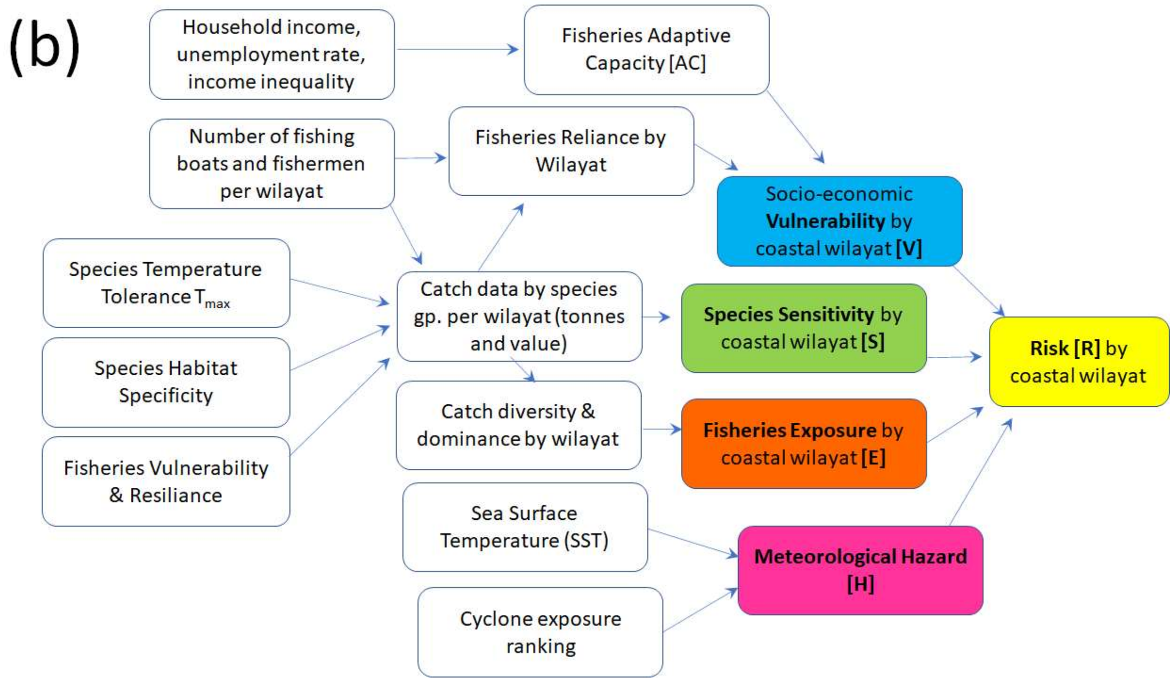


Figure 5. Schematic representation of how the Climate Risk Assessment (CRA) was constructed for (a) 49 fishing fleets and (b) 30 coastal wilayats (fishing districts) in the Sultanate of Oman

The primary data source used for the present CRA analysis is the annual collation of fisheries landings data, published every year by the General Directorate of Planning and Development – Fisheries Statistic Department (FSD), based on information from the Ministry of Agriculture, Fisheries and Water Resources. Given that the scale and composition of the fisheries in Oman have changed so markedly in recent years (with landings doubling between 2015 and 2019, and following advice from the Ministry of Agriculture, Fisheries and Water Resources – Directorate General of Fisheries Research), it was decided that we should base all analyses on averages for the past four years (2016-2019). The one exception to this is the scoring of hazard [H] exposure [E] and vulnerability [V] for the new horse mackerel fleet, whereby data were only available for the most recent year (2019).

The Ministry of Agriculture, Fisheries and Water Resources – Directorate General of Fisheries Research regularly monitors landings of marine fish in Oman and releases these datasets on an annual basis as *Fisheries Statistics Yearbooks.* Within these yearbooks, data are presented for the artisanal fleet, but also for the much smaller ‘coastal’, and industrial fleets, as well as for aquaculture. Each yearbook includes a full breakdown of monthly and yearly landings for 150 commercially “most important” fish and shellfish species caught by the artisanal fleet, but these are not themselves, ascribed to individual fleets or different parts of the country. Instead, more aggregated data (for 39 fish species or groups of species) is available for different fleet segments, and only data on the number of fishermen, boats and total landings (in tonnes) is available at the wilayat (district) level. Hence, a series of data manipulations, and some assumptions, have been necessary to obtain all of the datasets used in the CRA analysis.

In the CRA 'Fishing fleets' are defined based on a combination of: (1) fishing sector – artisanal, coastal or industrial; (2) governorate; and (3) gear type. For artisanal fleets, yearbook data are provided for 13 different gear types:

- LA (BSN)
- LA (FT)
- LA (HL&TL)
- LA(NET)
- BSN
- FG(FT)
- FG(NET)
- FG(HL&TL)
- FG(Shrimps-Trowler)
- FG(CuttleFish+Squid)
- FG(Lobster)
- FG(Small Pelagic Net)
- FG(CN)

Where LA = Wood or fiberglass dhow vessels between 10 and 30 meters (inboard engine); FG = fibreglass vessels with outboard engine (10-42 feet) i.e. 'skiffs'; BSN = Beach seine net; FT = Fish trap, HL = Hand line; TL = Troll line, CN = Cast net.

For industrial fleets, it is assumed that the vast majority of catches (primarily large pelagic species) are taken by longline fishing. However, an additional industrial fleet has been added to our analyses to represent the new horse mackerel fishery. In total 49 individual fleet segments have been considered in the analysis.

In addition, analyses have been conducted for 30 coastal wilayats (districts): 3 in Musandam [MUSA] Governorate, 8 in Al-Batinah North & south [ABNS] Governorate, 5 in Muscat [MUSC] Governorate, 4 in Al-Sharqiyah South [SHAS] Governorate, 3 in Al-Wusta [AWUS] Governorate and 7 in Dhofar [DHOF] Governorate.

5.1 Species Sensitivity [S]

In order to assess each species' sensitivity to climate change, we compiled information on their biological traits with special emphasis on characteristics that are related to temperature preferences, vulnerability to fisheries and/or other disturbances, mobility, and degree of habitat specificity. This approach was adapted and modified from Hare et al.'s (2016) climate vulnerability assessment of fish and invertebrates on the Northeast U.S. Continental Shelf. The information on biological traits was compiled from Fishbase (accessed May 2020) Aquamaps (accessed May 2020), and Cheung et al. (2013). Systematic information on the following biological attributes was scored, and for each of these a 'trait sensitivity score' was attributed between 1 (low sensitivity) and 4 (high sensitivity):

Tolerance to high temperatures. Information on species' temperature preferences were taken from Aquamaps (accessed May 2020), where modelled 'native range data' for fish species were collated (see http://www.aquamaps.org/AboutAquaMaps.htm). This is based on long-term annual mean sea temperature for all half-degree latitude–longitude grid cells, where a given species has been 'observed' according to OBIS (Ocean Biodiversity Information System) or GBIF (Global Biodiversity Information Facility) species occurrence records (for pelagic species, sea surface temperature is used; for non-pelagic species, sea bottom temperature is used). Data on minimum and maximum temperature, and 'minimum and maximum preferred temperature' (defined as the 10th and 90th percentile temperature, TP10 and TP90, respectively) were downloaded. In the study area, mean sea temperatures are high compared to most species' observed tolerance ranges (e.g., cf. Cheung et al., 2013). Given that temperatures are predicted to increase further (see figure 3), the 'maximum preferred temperature' (90th percentile of a species' full temperature range, TP90) was used to assess a species' tolerance to high temperatures where a score of sensitivity was scored as follows: TP90 ≥ 29.17°C, score 1 (very high tolerance to high temperatures); TP90 range 29.0–29.17°C, score 2 (high tolerance); TP90 range 28.7–28.9°C, score 3 (medium tolerance); TP90 < 28.7°C, score 4 (low tolerance). Aquamaps data on thermal tolerances was available for every species, with the exception of the endemic abalone *Haliotis mariae* and the horse mackerel *Trachurus indicus. Haliotis mariae* is only found in cooler waters, associated with seasonal upwelling along the shores of Dhofar Governorate in Oman. Values for upper temperature tolerances were obtained from the from the growth study of Shepherd et al. (1995). For *Trachurus indicus* it was assumed, based on fisheries surveys of the Omani coast that this species has a similar distribution, and hence temperature preferences to *Sardinella gibbosa*, Goldstripe sardinella (Strømme 1986). There remains a lack of basic biological information on this important species.

Habitat specificity. - Species with spatially restricted habitat requirements during part of their life-history will be more sensitive to climate change than those with less specific habitat requirements (Rijnsdorp et al., 2009), even if such specific habitat requirements are mainly evident during particular, critical stages within a species' life-history (Petitgas et al., 2013). For the 150 species examined here, information on traits related with habitat specificity was collated from Fishbase (accessed May 2020). We distinguished between 'horizontal habitat', ranging from coastal to oceanic, and 'vertical habitat', which accounts for their position in the water column, as defined in Ellis et al. (2011) and Engelhard et al. (2011). 'Horizontal habitat preference included': oceanic (often globally distributed); shelf (offshore species associated with either the continental shelf, or with sea areas near islands less than 200 m deep); slope (off the continental slope, or near islands at greater depths); coastal (generally living nearshore); and reef-associated (typically occurring in close association with reefs). It should be noted that naturally there is overlap between these habitats and species may move in and out, or shift according to life-stage. 'Vertical habitat preference' included: pelagic (in water column), epipelagic (in uppermost layers of water column, especially in case of oceanic species), benthopelagic (either in water column or near the seabed), demersal (near the seabed), and bathydemersal (living close to the seabed at great depths). We also scored 'mobility', either as highly migratory (individuals ranging over 100s–1000s of km), mobile (ranging over 10s of km), or sedentary (ranging within a few km). For each species, 'overall habitat specificity' was derived by combining information on mobility, horizontal and vertical habitat preferences, and scored as follows:

- Low (score 1): oceanic, epipelagic, highly migratory/mobile species; and slope, bathydemersal, mobile species;

- Medium (score 2): coastal/shelf, pelagic/benthopelagic/demersal, mobile species;
- High (score 3): reef-associated, epipelagic/pelagic/benthopelagic/demersal, mobile species;
- Very high (score 4): reef-associated, demersal, sedentary species.

Population resilience to fishing. – Stocks that are subject to intense exploitation will be more vulnerable to climate change in comparison with those experiencing low fishing pressure (Rijnsdorp et al., 2009). Sensitivity to fishing can be elevated if a species suffers reduced abundance, age and size truncation and hence reduced reproductive potential, reduced genetic variability, and hence limited possibilities to adapt to climate change (Ottersen et al., 2006; Anderson et al., 2008). Moreover, fish and shellfish species differ in the extent to which their populations may withstand varying levels of exploitation. 'Population resilience to fishing' is strongly associated with productivity-related traits such as the age at first reproduction, fecundity, intrinsic rate of increase r, growth curve model (von Bertalanffy k), and maximum age and size (Musick, 1999). The American Fisheries Society suggested several metrics that allow us to classify a fish population or species into categories of high, medium, low or very low resilience or productivity (Musick, 1999). Here, information on intrinsic 'population vulnerability to fishing' was collated from Fishbase (accessed December 2017–March 2018), based on approach proposed by Cheung et al. (2005). In this scheme, intrinsic vulnerability is a continuous variable that ranges from 0 to 100. It should be noted that vulnerability scores were available for all species except the abalone *Haliotis mariae* and blue swimmer crab *Portunus segnis*, where values were taken from closely related species *Haliotis midae* and *Macropipus puber,* respectively. For our purposes, the following four population vulnerability scores were distinguished: high to very high (score 1: vulnerability score >55); moderate to high (population vulnerability score 40-55); low to moderate (population vulnerability score 26-39); and low (population vulnerability score <25).

Overall species sensitivity. – For each species, an 'overall species sensitivity' score was then calculated to describe overall sensitivity to climate change. This was based on the unweighted mean of scores for high-temperature tolerance, overall habitat specificity, and intrinsic vulnerability to fishing. Given that individual trait sensitivity scores ranged between 1 and 4, the combined 'overall species sensitivity scores' will also have a potential range of 1 (indicating very low species sensitivity) to 4 (indicating very high species sensitivity).

Fleet or wilayat-level species sensitivity. – Based on the average (2016-2019) species composition of catches by fleet – obtained from yearbook data on landings, collated and provided by the Fisheries Statistic Department (FSD), the average species sensitivity was calculated for each of the 49 fishing fleets and 30 coastal wilayats (fishing districts). This was achieved by weighting each species' individual sensitivity score with the total catch for that species in a fleet or wilayat, and then dividing the sum of the weighted scores for all species by the total weight of all catches for that fleet or wilayat.

Because fleet-based landings data were only available in aggregated form (for 39 fish species or groups of species) it was necessary to split some of the 'bucket groups' in accordance with relative abundance (total landings) of relevant species in the country-wide long-list of 150 fish and shellfish. For example, fleet-based landings data were only available for rabbitfish (Siganidae), but this was subsequently split into three species *Siganus canaliculatus* (62.6%), *Siganus javus* (37.2%), and *Siganus sutor* (0.2%) and the overall sensitivity score scaled accordingly.

To obtain catch composition data for the artisanal and coastal long-line fleet in individual wilayats (districts), the total catch (of each species) by governorate was split in proportion to the number of fishing vessels present in each wilayat. For example, catches for the Musandam Governorate (1725 artisanal fishing vessels in total) were split into Bukha wilayat (10.0%, 173 vessels), Khasab wilayat (71.1%, 1226 vessels), and Daba wilayat (18.9%, 326 vessels).

The fleet or wilayat 'species sensitivity index' [S] was normalized and rescaled to range from 0 to 1, with higher values representing higher levels of sensitivity, as advocated by Allison et al. (2009).

5.2 Fisheries Exposure [E]

Many authors have argued that fleets, ports or fishing communities have higher resilience if they catch a wide range of fish species, rather than concentrating on a specific resource. To calculate such indices for Oman we made use of the catch statistics provided by the Fisheries Statistic Department (FSD). These were aggregated to the fleet or wilayat level but only broken down in accordance with the standard 39 fish species or groups of species that are used each year for reporting purposes. Following this, two indices were calculated, "**Shannon diversity of fisheries landings**" and "**Simpson's dominance of fisheries landings**".

The Shannon statistic (H') is one of the most commonly used diversity indices in ecology. The formula for calculating the index is:

$$H' = -\sum p_i \ln p_i$$

Equation 1

Where n_i is the biomass of each species, N is the total biomass of all species, p_i (the proportional abundance of the ith species = $\left(\frac{n_i}{N}\right)$

Simpson's dominance index (D) is another widely used statistic which, as the title implies, emphasizes the relative abundance of the commonest species in the sample, i.e. it measures the degree of dominance by a few key species. As D increases, dominance increases and therefore evenness and diversity decreases. The equation and calculation are as follows:

$$D = \sum \frac{n_i(n_i - 1)}{N(N - 1)}$$

Equation 2

Note that, in the present analysis, high diversity (H') of landings at the fleet or wilayat level is thought to characterize communities that are less sensitive to climate change and cyclone disruption whereas, fleets or wilayats that exhibit higher dominance (D) are thought to be more sensitive and hence these two indices have been scaled accordingly. A composite index of exposure [E] was calculated as an unweighted average of the indices described above. Resulting values were normalized and scaled to range from 0 to 1, with higher values reflecting greater sensitivity.

5.3 Fisheries Vulnerability [V]

In this analysis we have followed the approach taken by Colburn et al. (2016) and have interpreted this component of the overall risk assessment as **the relative reliance within the community or fleet on fisheries to provide employment, income or food security**. Communities are more likely to be sensitive to climate change if they are highly dependent on a climate-vulnerable natural resource (Cinner et al. 2013) and have limited ability to adapt (low 'adaptive capacity').

Very little information is available within the Fishery Statistics yearbooks at the level of individual fishing fleets. However, aggregate information is typically available on the composition of fisheries catches (in tonnes), the number of boats within each fleet, and the fishing effort expended (total number of fishing trips) each year. In addition, it has been possible to estimate the economic value (RO 1,000) of the catch by using the available catch composition data together with average price (value divided by tonnes) from the country-wide 'long list' of 150 commercial species in Oman. Hence, the primary metric used to characterise Vulnerability [V] for fishing fleets in Oman is based on the **economic revenue per vessel** (see equation 3). However, it makes very little sense to use these data in their raw state, as a single industrial vessel can catch many thousands of tonnes of fish in a year (and earn millions of Rial (OMR)) compared to only a few tonnes for a single artisanal boat or dhow, and it is not clear which of these vessel categories would leave people inherently more vulnerable to climate change. Therefore, we have chosen to divide economic revenue per vessel, by the average number of dependent crew members per vessel – to gain some appreciation of the social benefit. We assume that fleets with low **revenue per crew member** would be inherently more vulnerable to climate change than a fleet with higher revenue per crew member. The average number of crew members per vessel was determined by dividing the total number of fishermen employed in the artisanal sector in 2019 (50,405) by the total number of vessels (25,030) = 2.01. By contrast it is assumed that the average crew size of an industrial long-line vessel is 20 fishermen (see above), and the crew size of a 'coastal' vessel (typically 13 - 32 m in length) is ~8 (FSD 2019). For the new industrial horse mackerel fleet (a single 93 m long pelagic freezer trawler), a crew size of ~51 fishermen was assumed[1].

[1] http://www.seaboats.net/77m-pelagic-freezer-trawler-xidp412267.html

$$\frac{Total\ revenue\ for\ fleet \div Number\ of\ vessels\ in\ fleet}{Average\ number\ of\ crew\ members\ per\ vessel} = Revenue\ per\ crew\ member$$

Equation 3

For coastal Wilyats (districts) much more information is available with which to construct metrics of socio-economic vulnerability [V], hence a variety of different indicators that reflect both reliance on fisheries, but also socio-political characteristics of regional economies have been considered. We have taken a nested approach whereby we combine four indicators of reliance on fisheries into a single metric [F] and three indicators of adaptive capacity into a single metric [AC] that are then combined into the final metric of vulnerability [V].

The four indicators of reliance on fisheries are:

- Fisheries landings (tonnes) per km coastline
- Fisheries landings (value) per km coastline
- Number of fishing vessels per km coastline
- Number of fishermen per km coastline

Among the Community Social Vulnerability Indicators (CSVIs) generated by Colburn et al. (2016) for the eastern USA, the total weight (tonnes) of landings in each community, and value (US$) of those landings were used as components of the 'Commercial fishing engagement index '. In the present analysis, fishery landings data (expressed in tonnes) were aggregated for each of the 30 coastal wilayats. To account for the very different geographic sizes of the 30 wilayats it was necessary to divide the total by the approximate relative length of the coastline (using the 'measure distance' tool in Google Maps), and this yielded an indicator of **"Fisheries landings (tonnes) per km coastline"**. This dataset was then used, together with fish prices to yield an indicator of **"Fisheries landings (value) per km coastline"**. It was assumed that wilayats with higher total landings (or value) per km are inherently more vulnerable than those with lower total landings or value. Similarly, an indicator of the **"Number of fishing vessels per km coastline"** and of **"Number of fishermen per km coastline"** was estimated based on data (concerning the artisanal fishery) contained in the 2019 Fisheries Statistics yearbook (FSD 2019; Table No.: 2 – 2). For the industrial fleet it was assumed that all longline vessels (3) and associated fishermen (60) could be ascribed to the Mutrah wilayat (Muscat Governorate), and that the horse mackerel fleet (1 vessel, 51 fishermen) could be ascribed to the Salalah wilayat (Dhofar Governorate). The 'coastal' fishing fleet (vessels 13 - 32 meters in length) has a high concentration in the Arabian Sea, and in particular from Ras AL Had in Sharqiya to Dhofar[2].

'Adaptive capacity' reflects peoples' ability to anticipate and respond to changes and to minimize, cope with, and recover from the consequences (Cinner et al. 2013). For example, people with low adaptive capacity may have difficulty adapting to cyclone events or temperature rise or taking advantage of opportunities created by changes in the availability of ecosystem goods and services stimulated by climate change. For most Climate Vulnerability Assessments (CVA) conducted so far, including Allison et al. (2009), indices of 'Adaptive capacity' have been based on the level of wealth

[2] https://www.iotc.org/sites/default/files/documents/2014/01/IOTC-2013-SC16-NR20.pdf

in a particular country or community. Among the Community Social Vulnerability Indicators (CSVIs) proposed by Colburn et al. (2016), four socio-economic metrics were developed, namely: a 'personal disruption index', a 'Poverty index', a 'labour force structure index' and a 'housing characteristics index'. In the present analysis for Oman, we have 'mined' government databases and reports in search of any datasets at the wilayat or Governorate level that could be used to assess adaptive capacity [AC]. The primary sources were the online portal of the National Centre for Statistics and Information (NCSI) (accessed August 2020) and the 2012 'Household Expenditure and Income Survey' published by the NCSI (NCSI 2012). The three indices of adaptive capacity used in the present analysis are:

- Unemployment rate (at the Governorate level)
- Average Household income (at the wilayat level)
- GINI index (at the Governorate level)

Information on the **unemployment rate** was obtained from the NCSI online data portal and was available for the four-year period spanning 2015 to 2018. The unemployed are people of working age who are without work and have taken specific steps to find work. The uniform application of this definition results in estimates of unemployment rates that are more internationally comparable than estimates based on national definitions of unemployment. This indicator is measured in numbers of unemployed people as a percentage of the labour force and it is seasonally adjusted. In the present case, we used the four-year average for each governorate (data on individual wilayats was not available), and we have assumed that all wilayats within a governorate have broadly the same unemployment rate. It was necessary to invert the scores so that the wilayats with the highest rate of unemployment had the lowest 'adaptive capacity'.

Several alternative data sources were available for information on **average monthly household income** (expressed in OMR). Information at the governorate level was available from the NCSI online data portal, but only for the year 2010. Similarly, governorate level data on 'Household monthly income inclusive of imputed owner-occupied rent' was available in the 2012 'Household Expenditure and Income Survey' published by the NCSI for the year 2010 (based on data collected between 20/05/2010 - 19/05/2011). However, data at the level of individual wilayats was published in Appendix 7-2 of a government report (MTC 2005) for the year 2010, and this was used in the CRA analysis (see figure 12). The fact that data were only available for 2010, and not a more recent period is unfortunate, but this is not too problematic empirically as the primary focus is not on absolute levels and is instead on the relative distribution across the different wilayats. It should be noted however, that the Al Batinah Region was split into Al Batinah North Governorate and Al Batinah South Governorate on 28 October 2011.

The **'GINI index'** is the most frequently used index of income inequality worldwide. It is developed from first drawing a Lorenz curve, showing the total national income held by each percentage of the population. If a country has perfectly equal income distribution, the Lorenz curve drawn would be a straight line with a 45- degree angle. It is expected in this case that the poorest 10% of population would have 10% of the income, the poorest 20% would have 20% of the income and so on. However, it is understood that no country can have perfectly equal income distribution.

The GINI coefficient, expressed as a percentage, falls between zero and 100%. Higher values of the coefficient mean more discrepancies in income distribution. A GINI value close to zero indicates a relatively equal distribution of income, while a GINI % close to 100 indicates a highly unequal income distribution in a society. In the present case, values of the GINI coefficient were available for the year 2010 at the governorate level in the 'Household Expenditure and Income Survey'. The GINI coefficient for Oman as a whole was estimated at 30.7%. We have assumed that all wilayats within a governorate have broadly the same GINI coefficient. However, it was necessary to invert the scores so that the wilayats with the lowest score (highest level of income inequality) had the least 'adaptive capacity'.

As always, each component metric was calculated as an unweighted average of the indices contained therein. Each underlying dataset was normalized and scaled to range from 0 to 1, with higher values reflecting greater adaptive capacity or fisheries reliance.

5.4 Meteorological Hazard [H]

'Hazard' is the degree to which a system (in this case fishing fleets or coastal fishing communities) is stressed by climatic factors, such as the magnitude, frequency, and duration of climatic events including temperature change or extreme weather (e.g. cyclones). In the present case it was assumed that the most important climatic variables that could have a bearing on 'risk' in the fisheries sector would be changes in sea surface temperature (SST) and changes in the magnitude or frequency of catastrophic storm events (cyclones). Temperature is already partly accounted for in CRA calculations, with temperature tolerances forming an important part of species sensitivity metrics [S]. However, it was felt useful to differentiate the various governorates (used to define fleets) and coastal wilayats of Oman in terms of the differing level of meteorological hazard they face, as environmental conditions in some areas of the country are much more benign than in others. Ocean acidity (pH) and oxygen concentrations were not considered in our analyses for fisheries, although low oxygen conditions were considered in the assessment for aquaculture (see section 8).

Seawater temperatures around Oman vary considerably, both in space and over time (seasonality) and this determines the distribution of commercial fish and shellfish species. Feary *et al.* (2010) surveyed reef fish communities at four sites within the southern Arabian Gulf, where sea-surface temperatures were considered 'extreme' (range: 12–35°C annually), and compared them with communities at four latitudinally similar sites in the biogeographically connected Sea of Oman, where conditions are more moderate (range: 22–31°C annually). Although sites were relatively similar in terms of coral cover, substantial differences in the structure and composition of fish assemblages were apparent. Consequently, the authors reasoned that there is potential for substantial changes in the structure of reef-associated fish communities in the future if seawater temperatures change.

On average, seawater temperatures around the Musandam Peninsula in the Straits of Hormuz are much warmer than anywhere else along the Omani coast, and this is especially so with respect to the Arabian Sea coasts (Al Wusta and Dhofar Governorates) where seawater temperatures are heavily influenced by the seasonal upwelling of cooler waters, associated with the Indian monsoon (see blue or green colours in figure 6). However, figure 7 shows that the seasonal temperature regime is also very different in Musandam Peninsula, where SST can range from 22°C in winter to 33°C in summer, compared to a bi-modal pattern along the southernmost coast of Oman. During the winter monsoon period, SST along the southern coast reduces from 26°C in November to 22–23°C in February. By contrast, with the onset of the summer monsoon, the temperature rises to ~28°C in May until upwelling dominates and temperatures in the upwelled areas drop below 22°C near the coast in August. The lower temperatures near the coast persist until the upwelling weakens in November and temperatures rise again, although on the whole temperatures are lower in the waters off Al Wusta and Dhofar Governorates compared to elsewhere in Oman (ROPME, 2013).

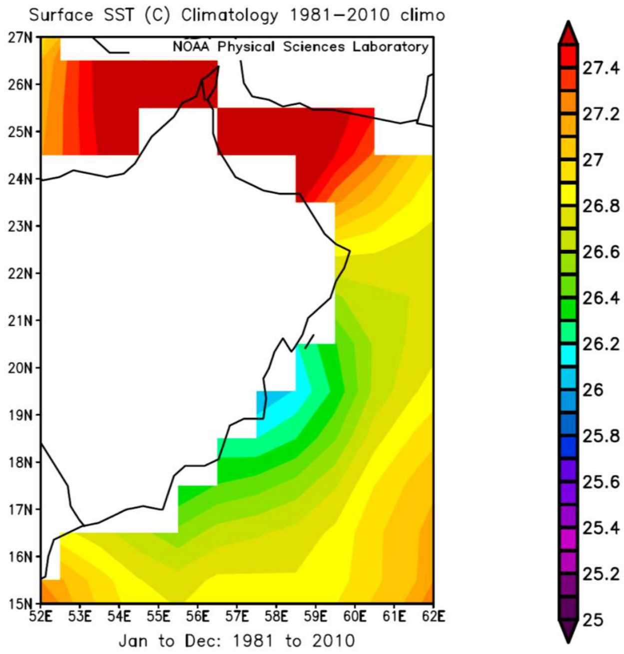


Figure 6. Sea surface temperature data (°C) from the NOAA OISST online portal, plotted showing the long term mean climatology (1981-2010).

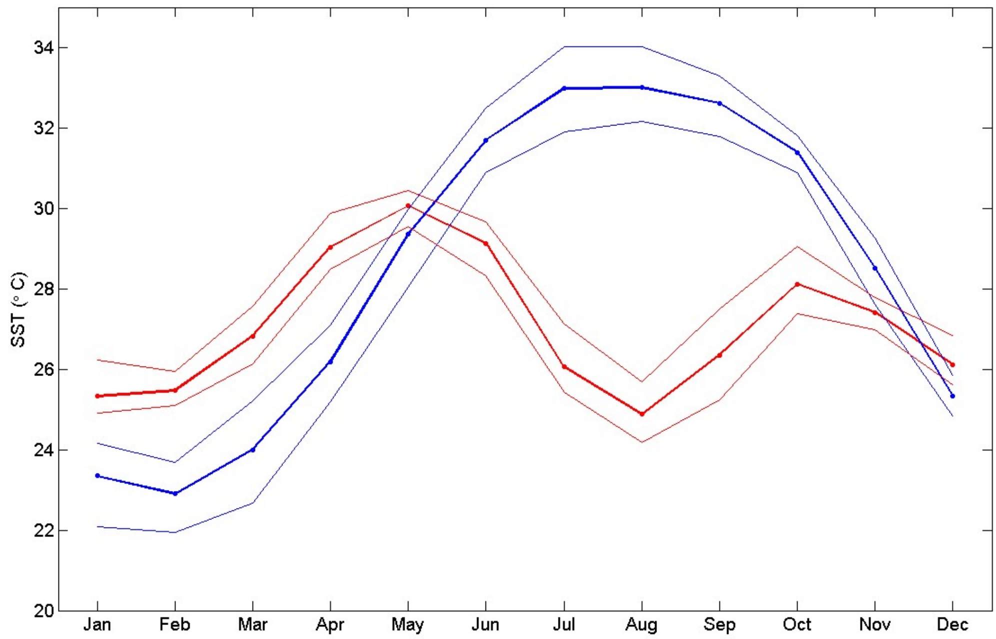


Figure 7. Annual mean sea surface temperature (°C) timeseries for 1 degree Lat/Long grid cells along the Oman coast. Northernmost cell (Strait of Hormuz) in blue, Southernmost (near Salalah) in red. Ranges show minimum and maximum for the past 10 years. Data from HadISST for 2010-2019.

In terms of long-term temperature change, analysis of the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST) has revealed that the governorate which experienced the most rapid rate of change in recent decades has been Ash Sharqiyah at the boundary between the Arabian Sea and the Sea of Oman (Pers. Comm. Michel Claereboudt, Sultan Qaboos University). However, future projections from climate models (e.g. figure 3) suggest that waters all around Oman will increase in temperature at a relatively uniform rate and could rise by as much as 2.6 to 2.8 °C by 2050–2099 under an RCP8.5 (high emissions) scenario, compared to the historical reference period (1956–2005), although of course this means that in absolute terms that seawater temperatures around the Musandam Peninsula could reach 36 °C and exceed the maximum tolerances of many, if not most commercial fish and shellfish species.

For purposes of the CRA analysis we used present-day sea surface temperatures from HadISST as the basis to differentiate different governorates and wilayats. It is assumed that more commercial fish species will come under pressure in the warmest areas of the coast (the level of 'hazard' is highest), whereas more species will be able to persist in cooler areas. For the fleet-based analysis, it was assumed that the various artisanal fleets obtain their catch in the vicinity (governorate) of the ports where they are based. For the 'coastal' fleet it was assumed that they primarily operate off the Al Wusta Governorate and the industrial long-line fleet primarily operates off Muscat Governorate (landing their catch in Mutrah). By contrast, it is assumed that the new horse mackerel fishery primarily operates in waters off Dhofar Governorate (landing their catch in Salalah). The average (annual) SST assumed for each governorate are as follows:

- Musandam Governorate = 28.77 °C
- Al Batinah Governorate = 28.76 °C
- Muscat Governorate = 28.21°C
- Ash Sharqiyah South Governorate = 27.08°C
- Al Wusta Governorate = 26.50°C
- Dhofar Governorate = 27.05°C

For analysis of coastal wilayats it was originally hoped to obtain high-resolution spatial data on average sea surface temperatures, however this has proven challenging for the moment. Therefore, we have used the governorate-level temperatures (above) for the analysis of risks to coastal communities, assuming that all wilayats within a Governorate exhibit similar average temperatures. It may be possible to revisit this assumption in the near future, should high-resolution data become more readily available. The governorate level temperature data (above) were normalized and rescaled to range from 0 to 1, with higher values representing higher levels of hazard, as advocated by Allison et al. (2009).

Another important meteorological factor to consider, in terms of possible future impacts on fishing fleets and coastal communities is the incidence or magnitude of periodic cyclone events. Considerable damage occurred to fishing vessels and onshore fisheries infrastructure during the passage of previous severe storm events. Cyclones generally approach the coast of Oman from the southwest (see figure 8) (Evan & Camargo 2011; Fritz et al. 2010). On average, storms strike Oman once every three years, mostly between Masirah Island and Salalah (Al Wusta Governorate), and usually before June or after October. About once every five years, a storm affects the Dhofar region of southern Oman, and Oman's capital of Muscat about once every ten years. Oman's most damaging storm was Cyclone Gonu in 2007, which was the strongest recorded storm in the Arabian Sea and the strongest to make landfall.

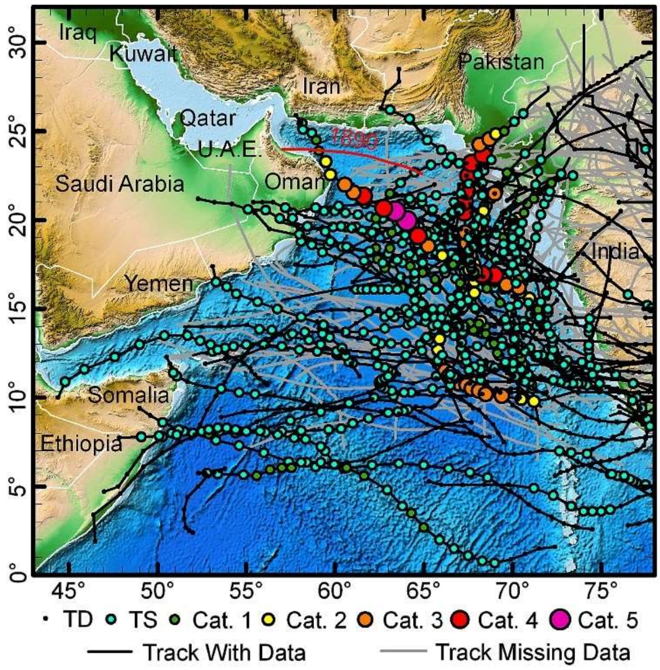


Figure 8. Storm track data for the Arabian Sea from the IBTrACS database. The track of the 1890 cyclone (shown in red) is based on historical documents. Note the 2007 cyclone Gonu track is the only confirmed category 5 storm to impact the Sultanate of Oman (from Fritz et al. 2010).

The relative ranking of cyclone exposure (hazard) for the governorates of Oman is:

1. Al Wusta Governorate
2. Ash Sharqiyah South Governorate
3. Dhofar Governorate
4. Muscat Governorate
5. Al Batinah (South) Governorate
6. Musandam Governorate

This ranking was used as the basis for the second indicator representing meteorological hazard [H]. The inverse ranking score was normalized and rescaled to range from 0 to 1, with higher values representing higher levels of hazard, as advocated by Allison et al. (2009) and the lowest value for Musandam Governorate representing the lowest level of hazard. We assumed that all wilayats within a Governorate exhibit similar cyclone exposure levels: although in reality, the most exposed wilayats are probably Duqm and Mahout (Al Wusta Governorate).

The overall metric for meteorological hazard [H] was calculated as the unweighted mean of the sea surface temperature indicator (see above) and the cyclone exposure indicator.

5.5 Construction of the overall 'risk' metric [R]

The attributes of risk, i.e. species sensitivity [S], fisheries exposure [E], fisheries vulnerability [V] and meteorological hazard [H] may be combined in many ways (see Allison et al. 2009) and this will be highly context-specific (Turner et al. 2003). Allison et al. (2009) explored the robustness of calculating vulnerability scores according to different methods of combining and weighting exposure, sensitivity and adaptive capacity into a composite index. Different methods of calculation had little effect on the rank order of resulting vulnerability scores. Both the weighted (i.e. one-half AC and one-quarter each for E and S) and unweighted vulnerability scores were highly correlated. In the present analysis, risk scores [R] for fishing fleets and coastal wilayats were calculated as **an unweighted mean of all four components S, E, V and H.**

6 Fisheries Assessment - Fishing Fleets Results

6.1 Species Sensitivity [S]

Tolerance to high temperatures. – The maximum preferred temperature (TP90) of 150 species was examined based on the landings statistics from Oman and their observed distribution within Aquamaps. The average figure was 28.8°C, with a range between 26.0–29.8°C (for a full overview, see appendix Table 1). For five species – blue swimmer crab *Portunus segnis,* blueline snapper *Lutjanus coeruleolineatus,* Sohal surgeonfish *Acanthurus sohal,* sand bird octopus *Amphioctopus aegina* and blackspot snapper *Lutjanus ehrenbergii* – the TP90 was >29.5°C indicating tolerance to high temperatures. Those species with the highest temperature tolerances were generally reef-associated fishes but also some very tolerant invertebrate species (crustaceans and cephalopods). By contrast, thirteen species showed very low warm-water tolerance (TP90 below 28°C), including Wahoo *Acanthocybium solandri*, dolphinfish *Coryphaena hippurus*, bluefish *Pomatomus saltatrix* and – chub mackerel *Scomber japonicus*, oceanic species with combined tropical and temperate distribution ranges but also some croakers (e.g. geelbeck croaker *Atractoscion aequidens,* cassava croaker *Pseudotolithus senegalensis,* fusta drum *Umbrina ronchus*). The species with the lowest temperature tolerance was the abalone *Haliotis mariae.*

Habitat specificity. – Of the 150 key commercial fish and shellfish species, twenty were oceanic, epipelagic, highly migratory or mobile fishes with very wide distribution ranges, and scored as having ***low*** overall habitat specificity (score 1; see Appendix table 1). These included dolphinfish, seven tuna species and relatives (including yellowfin, longtail, kawakawa and skipjack tuna, and kingfish and wahoo), three billfishes (*Xiphias gladius, Makaira indica* and *Istiophorus platypterus*), some oceanic elasmobranchs (*Aetobatis narinari, Sphyrna lewini, Alopias pelagicus*) and jobfishes (*Pristipomoides typus, Pristipomoides filamentosus, Pristipomoides multidens*). A ***medium*** overall habitat specificity was scored for 73 coastal and shelf species, mobile to highly migratory, which might be seen near reefs but are generally considered more as open-water species. These included various small pelagics e.g, Indian oil sardine *Sardinella* *longiceps*, horse mackerel *Trachurus indicus*, Indian mackerel *Rastrelliger kanagurta*, catfish *Arius tenuispinis* many small jacks and scads, as well as the Pharaoh cuttlefish *Sepia pharaonic*. A ***high*** overall habitat specificity was scored for 38 species associated with reefs, but mobile (generally pelagic, epipelagic or benthopelagic); these included many goatfishes, emperors, barracudas and large jacks. A ***very high*** habitat specificity was scored for 20 reef-associated, sedentary, demersal species: including lobsters, abalone *Haliotis mariae*, many groupers and snappers.

Population vulnerability. – Of all species examined, 30 were classified as having ***high to very high*** population vulnerability (scores >55) to fishing (following criteria proposed by the American Fisheries Society [AFS]; outlined in Cheung et al. (2005)): including many sharks, large jacks and groupers (see Appendix table 1). The species identified as being most vulnerable to fishing were honeycomb stingray *Himantura uarnak*, giant trevally *Caranx ignobilis* and scalloped hammerhead shark *Sphyrna lewini*. Forty-two species were characterised by ***moderate to high*** population vulnerability (scores 40 to 54). Fifty-one species were characterised by ***low to moderate*** population vulnerability to fishing (scores 26 to 39); these included many snappers, emperors and horse mackerel *Trachurus indicus*. Twenty-eight species were categorised as having ***low*** population vulnerability (scores <25) and these included all species of sardine, most scads, anchovies and cephalopods (squids, octopus and cuttlefish).

Overall species sensitivity. – Overall species sensitivity – based on the unweighted means of scores for high-temperature tolerance, overall habitat specificity, and population vulnerability to fishing – ranged between 1.3 and 4.0 (total possible range is from 1 to 4) – see Appendix Table 1. The lowest sensitivity scores (1.33) were observed in small pelagic species, buccaneer anchovy *Encrasicholina punctifer*, bluestripe herring *Herklotsichthys quadrimaculatus*, white sardinella *Sardinella albella* and Bloch's gizzard shad *Nematalosa nasus*. The highest sensitivity scores (4.00) were observed in whitebarred rubberlip *Plectorhinchus playfairi*, oblique-banded grouper *Epinephelus radiatus* and minstrel sweetlips *Plectorhinchus schotaf*. Table 1 gives the assigned sensitivity scores according to landing categories, as reported in *Fisheries Statistics Yearbooks.*

Table 1. Standardized climate sensitivity scores for species or species groups used in official catch statistics (those reported in *Fisheries Statistics Yearbooks*). Note that ‘Other small pelagics’ comprises predominantly horse mackerel *Trachurus indicus.*

LANDING CATEGORY	SENSITIVITY SCORE
Ribbonfish	3.33
Barracuda	3.08
Sweetlips	3.05
Abalone	3
Needlefish	3
Sailfish	3
Sharks	2.89
Croaker	2.82
Seabream	2.78
Large jacks	2.75
Other large pelagics	2.72

Grouper	2.7
Cobia	2.67
Yellowfin tuna	2.67
Catfish	2.66
Other demersal	2.53
Kingfish	2.34
Other small pelagics	2.34
Frigate tuna	2.33
Skipjack	2.33
Striped bonito	2.33
Queenfish	2.3
Rays	2.29
Cuttlefish	2.28
Emperor	2.25
Mullets	2.23
Lobster	2.02
Longtail tuna	2
Small jacks	1.95
Snapper	1.95
Sardine	1.92
Shrimp	1.91
Rabbitfish	1.88
Indian Mackerel	1.67
Kawakawa	1.67
Other	1.66
Anchovy	1.33

Fleet-level species sensitivity. – Based on the species composition of catches by fleet (combination of governorate and gear type), and the climate sensitivities of all landing categories (Table 1), the average species sensitivity [S] for each fleet-type was calculated (see table 2). The three fleets identified as having the highest species sensitivity scores (>2.80) were: MUSC-ART-LA(HL&TL), ABNS-ART-LA(HL&TL) and MUSA-ART-LA(HL&TL) all hand line and troll line dhow fleets targeting groupers, seabreams and sharks. By contrast the 8 fleets identified as having the lowest species sensitivity scores (<1.95) all targeted small pelagic fish such as sardines and anchovies or shrimps using beach seine nets or other pelagic fishing gears. These fleets were: ABNS-ART-BSN, MUSC-ART-BSN, AWUS-ART-FG(Shrimp), DHOF-ART-BSN, DHOF-ART-FG(CN), AWUS-ART-FG small-pelage Net, and SHAS-ART-FG small-pelage Net. It is interesting to note that 'coastal' long-line fleet ranked only 18th highest in terms of sensitivity scores, the 'industrial' long-line fleet ranked 19th and the 'industrial' horse mackerel fishery ranked 25th (out of 49).

6.2 Fisheries Exposure [E]

Fisheries 'exposure' is measured as the average Shannon diversity (H') and Simpson's dominance (D) of the reported fisheries catches by fleet over the four years 2016-2019. Figure 9 shows that these two indices are closely related but not linearly so. The four fishing fleets identified as having the highest catch diversity (and hence the lowest dominance) were: MUSC-ART-FG(NET), ABNS-ART-FG(NET), the 'Coastal' long-line fishery and AWUS-ART-LA(NET). In fact, the majority of fleets with diverse catches were artisanal net fishing fleets, but also some hand line and troll line vessels. By contrast, the five fleets with the least diverse reported catches (and hence the highest dominance) were: ABNS-ART-LA(FT), ABNS-ART-LA(HL&TL), the industrial horse mackerel fleet, MUSC-ART-LA(FT) and MUSC-ART-LA(HL&TL) for which only one species or species-group was reported in the official landings dataset, these were grouper, sharks, horse mackerel, seabream and sharks respectively.

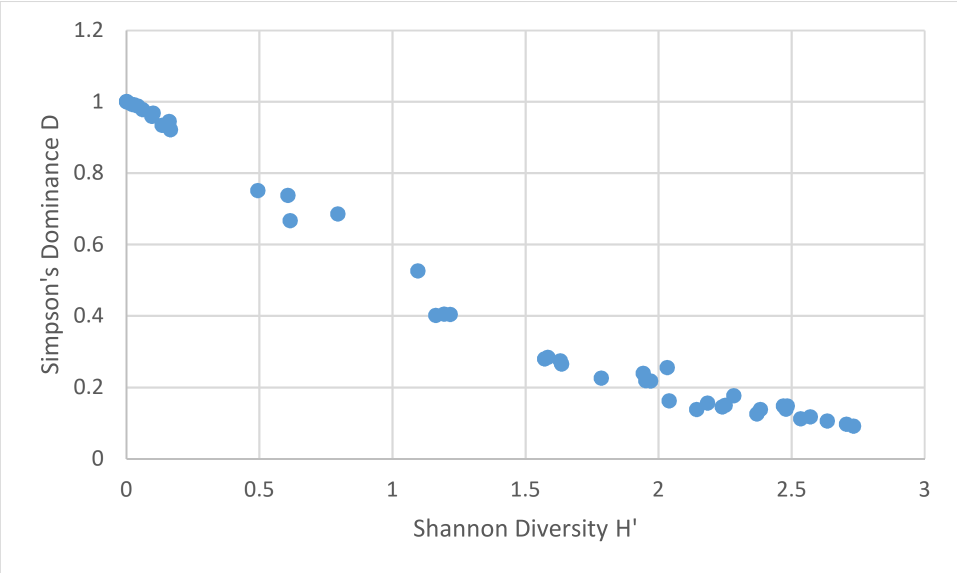


Figure 9. Relationship between the Shannon Diversity *H'* of fishery catches and the Simpson's Dominance *D*, for 49 fishing fleets in Oman based on average values for 2016-2019.

6.3 Fisheries Vulnerability [V]

In the present CRA analysis, the primary metric used to characterise Vulnerability [V] for fishing fleets in Oman was based on the **economic revenue per fishman** (measured in OMR 1,000s per year). For the vast majority of the artisanal fleets this value was relatively low (see table 2) and ranged from 0.2 to 4.0. However, some artisanal fleets earned higher revenues, notably many of the beach seine fleets: DHOF-ART-BSN (RO 22.6K), MUSA-ART-BSN (RO 6.33K), MUSC-ART-BSN (RO 5.22K), ABNS-ART-BSN (RO 3.99K) as well as the 'coastal' long-line fleet (4.80K). Most notably however, the industrial horse mackerel fleet earned the highest revenues (OMR 188.7K), followed by the industrial long-line fleet (OMR 26.2K per year) and hence these would be viewed as having the lowest fisheries vulnerability to climate change (or rather, the highest adaptive capacity). The fleets with the lowest revenues, and hence the least adaptive capacity were: MUSA-ART-LA(HL&TL) (OMR 0.29K), ABNS-ART-FG(FT) (OMR 0.34K), ABNS-ART-LA(HL&TL) (OMR 0.39K), MUSC-ART-LA(HL&TL) (OMR 0.4K). Because the resulting economic values were highly skewed, it was necessary to assign an inverse rank to these data which were then normalized and rescaled to range from 0 to 1, with higher values representing higher values levels of vulnerability [V] (see table 2).

6.4 Meteorological Hazard [H]

For purposes of the CRA analysis we have used present-day sea surface temperatures (SST) from HadISST as the basis to differentiate governorates. Each fishing fleet is defined by the governorate within which it is based (and presumably where it operates). Average annual sea temperatures ranged from 26.50°C for Al Wusta Governorate to 28.77 °C for Musandam Governorate. Raw temperature data were normalized and rescaled to range from 0 to 1, with higher values interpreted as representing higher levels of hazard. Similarly, the relative ranking of cyclone exposure was used, whereby Al Wusta Governorate experiences the most cyclones and Musandam Governorate the fewest. These ranks which were then normalized and rescaled to range from 0 to 1, with higher values representing higher values levels of implied hazard. An unweighted mean of the normalised temperature hazard scores and the cyclone hazard scores was used as the basis for the overall meteorological hazard [H]. Fleets in Al Batinah (South) Governorate were suggested to be exposed to the highest overall meteorological hazard, and those in Dhofar Governorate the least. It is interesting to note that the cyclone and temperature hazard indices seem to have an inverse relationship to one another, and hence Al Batinah (South) Governorate which is neither the warmest nor the most affected by cyclones emerges as having the highest hazard score [H] overall.

6.5 Overall Risk Score

Overall, the four fishing fleets that emerged as the **most at risk from climate change were the dhow fleets, ABNS-ART-LA(HL&TL), MUSC-ART-LA(HL&TL), MUSC-ART-LA(FT) and ABNS-ART-LA(FT)** (see table 2), using either fish traps (FT) or hand line and troll line (HL&TL). It should be noted however, that the overall scores in Table 2 reflect a fine balance between each of the components (S, E, V and H) such that a fleet can attain a moderate risk score overall, despite ranking highest or lowest in one or more of the four constituents. The fleets identified as least at risk from climate change were: MUSA-ART-BSN, DHOF-ART-FG(FT), DHOF-ART-BSN, MUSC-ART-BSN (see figure 11), and DHOF-ART-LA(NET), DHOF-ART-LA(HL&TL) i.e. they were often in Dhofar Governorate and/or using beach seines. It is also notable that the 'coastal' long-line fleet was identified as 3rd least at risk, and industrial horse mackerel fleet also received a low score.

Figure 10. Fishing traps on a fibreglass vessel at Al Seeb (Muscat Governorate). This is part of the fleet defined as MUSC-ART-FG(FT) that is identified as having a medium overall risk to climate change.

Figure 11. The beach seine fishery at Shati Al Qurum (Muscat Governorate). This is one of the fleets (MUSC-ART-BSN) that has been identified as having the <u>lowest</u> climate change risk overall.

Table 2. Data used in the Climate Risk Assessment (CRA) for the 49 fishing fleets of Oman.

	Landings (MT)	SENSITIVITY BY FLEET	Num Boats	NUM FISHERS	REVENUE PER PERSON	Shannon Diversity H'	Simpson's Dominance D	INDEX	INDEX	INDEX	INDEX	INDEX
FLEET	AVERAGE	AVERAGE	AVERAGE	AVERAGE	RO 1000	AVERAGE	AVERAGE	[H]	[S]	[V]	[E]	RISK
ABNS-ART-BSN	20953.25	1.76	1097.00	2205.00	3.99	1.58	0.28	1.00	0.00	0.13	0.32	0.36
ABNS-ART-FG(FT)	5291.25	2.35	10155.00	20412.00	0.34	2.18	0.16	1.00	0.52	0.98	0.14	0.66
ABNS-ART-FG(HL&TL)	10490.50	2.49	9815.00	19728.00	0.84	2.38	0.14	1.00	0.65	0.63	0.09	0.59
ABNS-ART-FG(NET)	19287.00	2.20	20469.00	41143.00	0.57	2.71	0.10	1.00	0.39	0.81	0.01	0.55
ABNS-ART-LA(FT)	501.25	2.70	282.50	568.00	1.87	0.00	1.00	1.00	0.83	0.35	1.00	0.80
ABNS-ART-LA(HL&TL)	47.75	2.89	116.50	234.00	0.39	0.00	1.00	1.00	1.00	0.96	1.00	0.99
AWUS-ART-FG small-pelage Net	87546.00	1.93	1432.00	2878.00	2.64	0.10	0.97	0.45	0.15	0.27	0.96	0.46
AWUS-ART-FG(Cuttlefish)	3361.50	2.38	1748.00	3513.00	1.45	0.10	0.96	0.45	0.55	0.42	0.96	0.59
AWUS-ART-FG(FT)	2717.50	1.99	293.00	589.00	3.19	0.61	0.67	0.45	0.20	0.21	0.70	0.39
AWUS-ART-FG(HL&TL)	20534.75	2.63	8795.50	17679.00	0.98	2.25	0.15	0.45	0.77	0.56	0.12	0.47
AWUS-ART-FG(Lobster)	163.50	2.04	532.00	1069.00	0.65	0.06	0.98	0.45	0.25	0.75	0.98	0.61
AWUS-ART-FG(NET)	17909.25	2.18	7396.00	14866.00	0.48	2.03	0.26	0.45	0.37	0.90	0.22	0.48
AWUS-ART-FG-Shrimps	631.00	1.87	697.00	1401.00	1.45	0.13	0.93	0.45	0.10	0.44	0.94	0.48
AWUS-ART-LA(HL&TL)	357.00	2.34	71.50	144.00	3.85	0.49	0.75	0.45	0.51	0.17	0.77	0.47
AWUS-ART-LA(NET)	16599.00	2.65	2409.25	4843.00	1.97	2.57	0.12	0.45	0.79	0.33	0.04	0.40
AWUS-COAST-LL	3251.25	2.45	111.75	894.00	4.80	2.63	0.11	0.45	0.61	0.10	0.03	0.30
DHOF-ART-BSN	6665.75	1.92	15.75	32.00	22.62	0.00	1.00	0.00	0.14	0.04	1.00	0.30
DHOF-ART-FG(CN)	13336.00	1.92	783.25	1574.00	0.91	0.03	0.99	0.00	0.14	0.58	0.99	0.43
DHOF-ART-FG(Cuttlefish)	2154.25	2.28	1731.25	3480.00	0.87	0.02	0.99	0.00	0.46	0.60	0.99	0.51
DHOF-ART-FG(FT)	10567.25	2.32	4297.75	8638.00	1.10	2.14	0.14	0.00	0.50	0.50	0.13	0.28
DHOF-ART-FG(HL&TL)	16627.75	2.59	13928.00	27995.00	0.51	2.53	0.11	0.00	0.73	0.85	0.05	0.41
DHOF-ART-FG(Lobster)	292.00	2.19	908.00	1825.00	0.67	0.61	0.74	0.00	0.38	0.73	0.74	0.46
DHOF-ART-FG(NET)	2855.00	2.29	1407.00	2828.00	0.56	1.95	0.22	0.00	0.47	0.83	0.21	0.38
DHOF-ART-LA(HL&TL)	1262.25	2.54	201.75	406.00	2.96	1.22	0.40	0.00	0.69	0.23	0.45	0.34

DHOF-ART-LA(NET)	1793.50	2.56	319.00	641.00	2.11	1.64	0.26	0.00	0.71	0.31	0.30	0.33
DHOF-INDUST(Horse Mackerel)	4811.75	2.34	1.00	51.00	188.71	0.00	1.00	0.00	0.51	0.00	1.00	0.38
MUSA-ART-BSN	15262.25	2.09	827.00	1662.00	6.33	2.37	0.13	0.45	0.29	0.06	0.09	0.22
MUSA-ART-FG(FT)	1788.50	2.49	2472.00	4969.00	0.60	2.04	0.16	0.45	0.65	0.77	0.17	0.51
MUSA-ART-FG(HL&TL)	3853.50	2.43	4431.00	8906.00	0.59	1.97	0.22	0.45	0.59	0.79	0.21	0.51
MUSA-ART-FG(NET)	9355.00	2.15	3830.00	7698.00	1.08	2.28	0.18	0.45	0.35	0.52	0.13	0.36
MUSA-ART-LA(BSN)	917.00	2.31	110.33	222.00	3.75	1.19	0.41	0.45	0.49	0.19	0.45	0.39
MUSA-ART-LA(FT)	622.75	2.69	439.00	882.00	1.51	1.09	0.53	0.45	0.82	0.40	0.54	0.55
MUSA-ART-LA(HL&TL)	79.25	2.84	178.00	358.00	0.29	0.79	0.69	0.45	0.96	1.00	0.68	0.77
MUSC-ART-BSN	4668.75	1.76	211.50	425.00	5.22	1.63	0.27	0.88	0.00	0.08	0.30	0.32
MUSC-ART-FG(FT)	890.25	2.37	1282.00	2577.00	0.45	2.24	0.14	0.88	0.54	0.92	0.12	0.61
MUSC-ART-FG(HL&TL)	6560.00	2.54	6773.00	13614.00	0.68	2.47	0.15	0.88	0.69	0.71	0.08	0.59
MUSC-ART-FG(NET)	10565.50	2.17	12147.00	24415.00	0.51	2.73	0.09	0.88	0.36	0.88	0.00	0.53
MUSC-ART-LA(FT)	21.00	2.75	13.75	28.00	1.32	0.00	1.00	0.88	0.88	0.46	1.00	0.80
MUSC-ART-LA(HL&TL)	5.75	2.89	13.25	27.00	0.40	0.00	1.00	0.88	1.00	0.94	1.00	0.95
MUSC-INDUST-LL	434.25	2.44	1.50	30.00	26.22	1.16	0.40	0.88	0.60	0.02	0.46	0.49
SHAS-ART-FG small-pelage Net	61787.25	1.93	1012.00	2034.00	2.68	0.16	0.94	0.60	0.15	0.25	0.94	0.49
SHAS-ART-FG(Cuttlefish)	1880.50	2.28	1969.50	3959.00	0.74	0.04	0.99	0.60	0.46	0.67	0.99	0.68
SHAS-ART-FG(FT)	2322.00	2.29	1032.50	2075.00	1.21	1.78	0.23	0.60	0.47	0.48	0.25	0.45
SHAS-ART-FG(HL&TL)	16362.50	2.59	7068.00	14207.00	0.98	1.94	0.24	0.60	0.73	0.54	0.23	0.53
SHAS-ART-FG(NET)	18860.00	2.25	7064.00	14199.00	0.82	2.48	0.15	0.60	0.43	0.65	0.08	0.44
SHAS-ART-FG-Lobster	110.75	2.10	320.00	643.00	0.69	0.16	0.93	0.60	0.30	0.69	0.93	0.63
SHAS-ART-FG-Shrimp	178.00	1.97	184.50	371.00	1.53	0.17	0.92	0.60	0.19	0.38	0.93	0.52
SHAS-ART-LA(HL&TL)	821.00	2.57	124.75	251.00	3.89	1.57	0.28	0.60	0.72	0.15	0.32	0.45
SHAS-ART-LA(NET)	12586.75	2.63	2286.00	4595.00	2.31	2.48	0.14	0.60	0.77	0.29	0.07	0.43

7 Fisheries Assessment - Coastal Districts (wilayats) Results

7.1 Species Sensitivity [S]

The same ranking of species sensitivity (Table 1) used for the fishing fleet analysis was used for the CRA of coastal wilayats (fishing districts), however the landings data were re-aggregated irrespective of the different fishing gears and fleets operating at a particular locality. Catch statistics for artisanal and 'coastal' longline vessels were first assembled at the total governorate level, but then split in proportion to the number of fishing boats operating in a given wilayat. What this means in reality is that the species sensitivity metric [S] is nearly always identical for all wilayats within the same Governorate. The two exceptions to this were Mutrah (Muscat Governorate) where catches from the 'industrial' longline vessels were added to the wilayat total, and Salalah (Dhofar Governorate) where catches from the 'industrial' horse mackerel fishery was added to the wilayat total.

Unfortunately, more highly resolved data were not available within the *Fisheries Statistics Yearbooks.* The scores for species sensitivity [S] by wilayat are shown in table 3. Sensitivity scores were remarkably similar across all Governorates (and hence wilayats), ranging from 2.11 to 2.32 (out of 4). This is because a wide portfolio of different fleets operate within each Governorate, including some targeting small pelagics, some targeting reef fish and some targeting tuna and other large pelagics. The wilayats identified as catching the most climate sensitive species were generally located in Dhofar Governorate and especially Salalah (Dhofar Governorate) where the horse mackerel fleet is currently based. By contrast, the wilayats identified as catching climate sensitive species the least were in Al Batinah Governorate.

7.2 Fisheries Exposure [E]

Because catch statistics for artisanal and 'coastal' longline vessels were first assembled at the total governorate level, but then split in proportion to the number of fishing boats operating in a given wilayat, the overall score for Shannon diversity *H'* and Simpsons Dominance *D* was also nearly always identical for all wilayats within the same Governorate (see table 3). The two exceptions to this were Mutrah (Muscat Governorate) where catches from the 'industrial' longline vessels were added in to the wilayat total, and Salalah (Dhofar Governorate) where catches from the 'industrial' horse mackerel fishery were added to the wilayat total. Diversity *H'* ranged from 1.52 (Salalah wilayat) to 2.95 (Mutrah wilayat) and was generally lowest in the Al Wusta and Ash Sharqiyah South Governorates, inferring higher exposure to climatic risks via the fishery. Conversely, dominance of particular species categories (*D*) was highest in the Al Wusta and Ash Sharqiyah South Governorates (and in Salalah), where small pelagic fish species (sardines, anchovy, horse mackerel) were a more prominent component of fish catches.

Table 3. Key indicators used for the Climate Risk Analysis (CRA) of 30 coastal wilayats in the Sultanate of Oman.

Governorate	Wilayat	Length of coastline (km)	Species sensitivity	*H'*	*D*	Average Landings (tonnes)	Average Landings (value)	Fishing boats per km	Fishermen per km	Monthly household Income/capita	GINI index	Unemployment rate
ABNS	Al-Khābūrah	12.2	2.11	2.79	0.07	4836.49	4864.68	37.45	75.27	71	28.5	3.31
ABNS	Al-Maṣna'ah [Musannah]	21.7	2.11	2.79	0.07	4995.94	5025.06	21.63	43.47	74	28.5	3.31
ABNS	As-Suwaīq	30.6	2.11	2.79	0.07	11214.28	11279.65	34.51	69.37	74	28.5	3.31
ABNS	Barka'	41.7	2.11	2.79	0.07	8982.05	9034.41	20.25	40.70	85	28.5	3.31
ABNS	Liwa	12.5	2.11	2.79	0.07	2094.04	2106.25	15.72	31.60	64	28.5	2.79
ABNS	Ṣaḥam	35.9	2.11	2.79	0.07	8142.31	8189.77	21.35	42.91	72	28.5	2.79
ABNS	Shināṣ	47.2	2.11	2.79	0.07	7143.13	7184.76	14.24	28.62	66	28.5	2.79
ABNS	Ṣuḥār [Sohar]	38.8	2.11	2.79	0.07	9162.76	9216.17	22.19	44.61	86	28.5	2.79
AWUS	Ad-Duqm	229.8	2.15	1.71	0.42	56886.18	21051.46	4.71	9.47	78	29.3	1.49
AWUS	Al-Jāzer	102.1	2.15	1.71	0.42	39289.81	14539.70	7.33	14.73	101	29.3	1.49
AWUS	Maḥūt [Mahout]	251.7	2.15	1.71	0.42	52106.27	19282.59	3.94	7.92	79	29.3	1.49
DHOF	Ḍalkūt [Dhalkut]	31.6	2.27	2.51	0.16	2612.78	1615.89	3.86	7.76	81	21.5	1.96
DHOF	Mirbāṭ	100.5	2.27	2.51	0.16	9958.56	6158.92	4.63	9.30	81	21.5	1.96
DHOF	Rakhyūt	47.2	2.27	2.51	0.16	1627.63	1006.62	1.61	3.24	81	21.5	1.96
DHOF	Sadaḥ	64.9	2.27	2.51	0.16	9230.40	5708.59	6.65	13.36	82	21.5	1.96
DHOF	Ṣalālah	72.5	2.32	1.52	0.44	29548.22	15994.84	6.65	14.04	101	21.5	1.96
DHOF	Shalīm & Juzur al-Ḥallāniyyāt	195.2	2.27	2.51	0.16	18610.72	11509.90	4.45	8.95	84	21.5	1.96
DHOF	Ṭāqah	10.8	2.27	2.51	0.16	3212.44	1986.75	13.88	27.89	81	21.5	1.96
MUSA	Bukhā	25.0	2.19	2.86	0.08	3174.07	2922.10	6.92	13.91	75	34.9	3.87
MUSA	Dibā al-Bay'a	59.0	2.19	2.86	0.08	5981.20	5506.38	5.53	11.11	84	34.9	3.87
MUSA	Khaṣab	411.4	2.19	2.86	0.08	22493.72	20708.03	2.98	5.99	89	34.9	3.87
MUSC	As-Sīb [Seeb]	45.9	2.20	2.88	0.07	5610.75	6169.88	10.93	21.98	153	29.7	0.60
MUSC	Bawshar	14.9	2.20	2.88	0.07	3107.15	3416.79	18.62	37.43	204	29.7	0.60
MUSC	Masqaṭ [Muscat]	50.1	2.20	2.88	0.07	6504.90	7153.13	11.63	23.37	154	29.7	0.60

MUSC	Maṭraḥ [Muttrah]	16.3	2.25	2.95	0.07	2928.43	3255.05	13.76	29.32	219	29.7	0.60
MUSC	Qurayyāt	68.6	2.20	2.88	0.07	4996.03	5493.90	6.52	13.10	116	29.7	0.60
SHAS	Ja'alan Banī Bū 'Alī	176.4	2.18	2.07	0.31	11143.69	4625.42	2.06	4.14	66	29.0	3.08
SHAS	Ja'alan Banī Bū Ḥassan	23.3	2.18	2.07	0.31	52525.79	21801.91	73.34	147.41	65	29.0	3.08
SHAS	Maṣīrah [Masirah]	162.7	2.18	2.07	0.31	31558.45	13098.99	6.32	12.70	72	29.0	3.08
SHAS	Ṣūr	117.4	2.18	2.07	0.31	22932.07	9518.43	6.36	12.79	89	29.0	3.08

7.3 Fisheries Vulnerability [V]

In the present CRA analysis for coastal wilayats in Oman, we used seven different indices for fisheries vulnerability [V], nested into two component metrics. We combined four indicators of reliance on fisheries into a single metric [F] and three indicators of adaptive capacity into a single metric [AC] that are then combined into the final metric of vulnerability [V].

Fisheries Reliance [F]

Our analysis has highlighted that some wilayats with very short coastlines can have substantial fishing fleets and are responsible for very large quantities of landed seafood, for example Ja'alan Banī Bū Ḥassan wilayat in Ash Sharqiyah South Governorate[3]. Overall the highest quantities of fish landed per kilometre of coastline were in the following coastal wilayats: Ja'alan Banī Bū Ḥassan (2251.43 t/km), Ṣalālah (407.62 t/km), Al-Jāzer (398.07 t/km) and As-Suwaīq (385.01 t/km). By contrast the least productive coastal wilayats were: Rakhyūt (34.51 t/km), Khaṣab (54.68 t/km), Ja'alan Banī Bū 'Alī (63.18 t/km) and Qurayyāt (72.87 t/km).

Similarly, in terms of economic revenue (measured in OMR 1000s per kilometre) the highest levels of total catch value were achieved for the wilayats: Ja'alan Banī Bū Ḥassan, Al-Khābūrah, As-Suwaīq and Ṣuḥār (934.50, 400.39, 368.98, 237.29 OMR 1000s respectively). The lowest levels of total catch value per kilometre were achieved for the wilayats: Rakhyūt, Ja'alan Banī Bū 'Alī, Khaṣab and Ḍalkūt (21.34, 26.22, 50.34, 51.12 OMR 1000s respectively).

With regard to the total number of fishing vessels and total number of fishermen per kilometre of coastline, the highest concentrations of fishing activity are located Ja'alan Banī Bū Ḥassan (73 boats/km, 147 fishermen/km), Al-Khābūrah (37 boats/km, 75 fishermen/km), As-Suwaīq (35 boats/km, 69 fishermen/km), Ṣuḥār (22 boats/km) and Al-Maṣna'ah (22 boats/km; 45 fishermen/km). Whereas the lowest level of fishing activity can be found in the vicinity of Rakhyūt (2 boats/km, 3 fishermen/km), Ja'alan Banī Bū 'Alī (2 boats/km, 4 fishermen/km), and Khaṣab (3 boats/km, 6 fishermen/km). It should be noted that the Khaṣab wilayat in Musandum consistently scored low in terms of fisheries activity per kilometre because of the very long (411 kilometres), fjord like coastline of this wilayat.

As always, each component metric was calculated as an unweighted average of the indices contained therein. Each underlying dataset was normalized and scaled to range from 0 to 1, with higher values reflecting greater fisheries reliance. The wilayats identified as having the highest reliance on fisheries [F] were: Ja'alan Banī Bū Ḥassan (score = 1.0), Al-Khābūrah (score = 0.39), and As-Suwaīq (score = 0.36).

Adaptive Capacity [AC]

The three indices of adaptive capacity used in the present analysis were:

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[3] https://www.omanobserver.om/jaalan-bani-bu-ali-where-fishing-thrives-and-holds-promise/

- Unemployment rate (at the Governorate level)
- Average Household income (at the wilayat level)
- GINI index (at the Governorate level)

Statistics suggest that the Governorate with the lowest unemployment rate (indicative of a higher adaptive capacity) is Muscat Governorate (0.6%), i.e. the capital city, where many alternative jobs are available and household incomes are typically higher (see figure 12). Rates of unemployment are higher elsewhere in the country, with the highest level of unemployment recorded in Musandam Governorate (3.87%), followed by Al Batinah South Governorate (3.31%) and Ash Sharqiyah South Governorate (3.08) (see table 3).

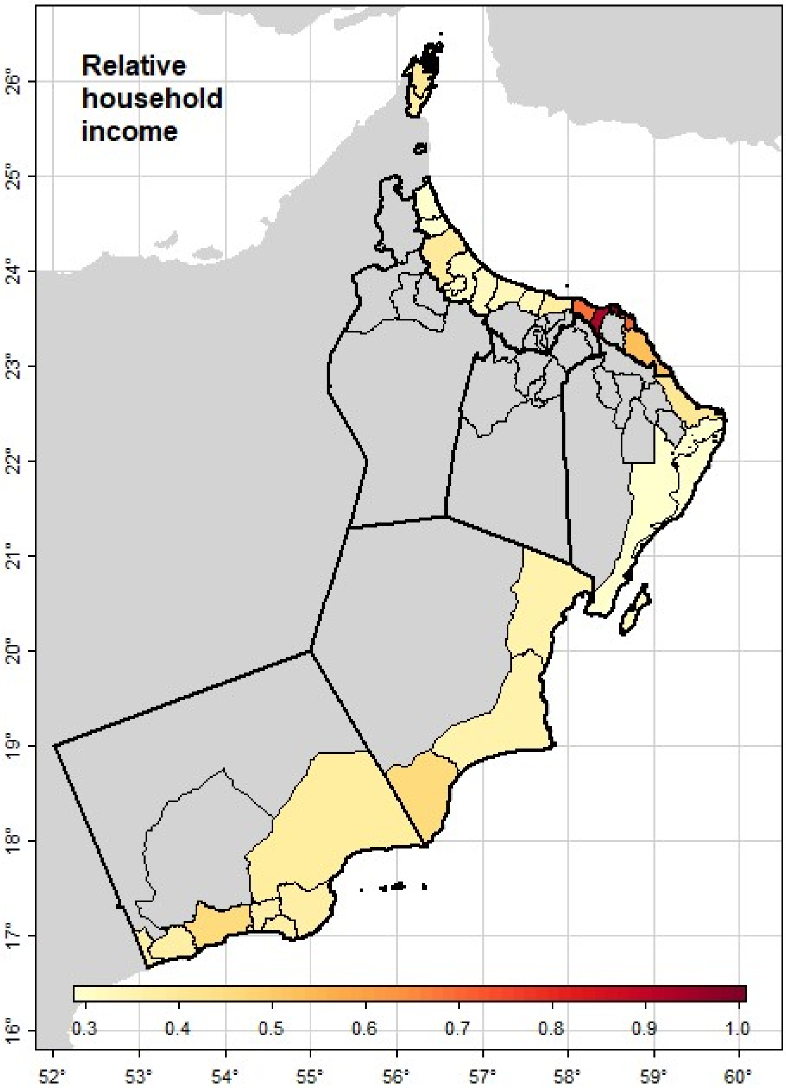

Figure 12. Relative household income by coastal wilayat

Data on monthly household income per capita (in 2010) was available for each individual wilayat, and this revealed that the highest incomes were predominantly found in wilayats near the capital city (Muscat Governorate), in particular Maṭraḥ, Bawshar and Muscat (monthly incomes OMR

219, 204, 154 RO respectively). By contrast the lowest monthly incomes tended to be observed in the Al Batinah North and Ash Sharqiyah North governorates, and in particular Liwa, Ja'alan Banī Bū Ḥassan, Shināṣ and Ja'alan Banī Bū 'Alī (OMR 64, 65, 66, 66 respectively).

Income inequality (as characterised by the GINI index) was highest in the Musundam Governorate (34.9%), followed the Muscat Governorate (29.7%) although these values are still lower than in many countries around the world. Higher GINI values infer a significant wealth gap between the richest and poorest members of society. Income inequality was lower elsewhere in Oman, particularly in Dhofar governorate (21.5%). It was assumed that highly unequal societies are more vulnerable to climate change pressures (see Islam and Winkel 2017), even though average incomes may be lower overall[4].

Each underlying dataset was normalized and scaled to range from 0 to 1, with higher values reflecting greater adaptive capacity (hence the GINI index and unemployment rate had to be inverted). The overall Adaptive Capacity [AC] metric was calculated as an unweighted mean of the three components. Following analyses of the datasets at the wilayat level, the three wilayats identified as having the lowest (least) adaptive capacity were all located in Musandam Governorate, namely Bukhā, Dibā al-Bay'ah and Khaṣab, closely followed by wilayats in the Al Batinah South Governorate and some in Ash Sharqiyah South Governorate. By contrast, the four wilayats identified as possessing the highest level of adaptive capacity from a socioeconomic perspective were all part of Muscat Governorate (Mutrah, Bawshar, Muscat and As-Sīb [Seeb] respectively).

The combined fisheries vulnerability score [V], was calculated as the unweighted mean of the F and (inverse) AC metrics. This revealed that the most vulnerable coastal wilayats overall, from a socioeconomic perspective are: Ja'alan Banī Bū Ḥassan, Al-Khābūrah, As-Suwaīq and Bukhā (see Table 4). The least vulnerable are Mutrah, Bawshar and As-Sīb (see Table 4 and figure 13).

7.4 Meteorological Hazard [H]

For analysis of meteorological hazard to coastal wilayats we assumed the same levels as for the fleet-based analysis (above). Wilayats were scored according to the prevailing sea surface temperature (SST) based on the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST), and a ranking (by Governorate) of cyclone exposure. As with the fleet-based analysis, wilayats in Al Batinah (North and South) Governorate were suggested to be most exposed to the meteorological hazard, and those in Dhofar Governorate the least (see figure 13). It should be noted that we have assumed that fishers operate in the seas broadly adjacent to the wilayat or Governorate in which they are based. This is probably a sensible assumption for small inshore artisanal boats (the vast majority), but may not be so appropriate for larger ‘industrial’ vessels. For example, the ‘industrial’ horse mackerel fishery is currently based in Ṣalālah wilayat (Dhofar Governorate) but is actually thought to operate all along the Al Wusta coast, and quite a long way

[4] https://www.un.org/esa/desa/papers/2017/wp152_2017.pdf

out from the shore. Indeed, the industry has stated that it intends to move its operations in the near future to new facilities in Ad-Duqm, Al Wusta Governorate.

7.5 Overall Risk Score

Overall, the four coastal wilayats that emerged as being the most at risk from climate change impacts on the fisheries sector were:

1. Ja'alan Banī Bū Ḥassan (score = 0.64)
2. Ṣalālah (score = 0.55)
3. Mutrah (score = 0.44)
4. Al-Jāzer (score = 0.41)

It is interesting to note that these four wilayats are in different Governorates of Oman (Ash Sharqiyah, Dhofar, Muscat and Al Wusta respectively) and that they amassed a high score for very contrasting reasons (see figure 13). Ja'alan Banī Bū Ḥassan received high scores for exposure, socio-economic vulnerability and hazard, whereas Ṣalālah received a very low score for hazard, but maximal scores for species sensitivity and exposure. Mutrah received a very low score for socio-economic vulnerability, but higher scores for species sensitivity and hazard. Al-Jāzer received a high score for exposure (landings dominated by a few species of small pelagic fish), and a low score for socio-economic vulnerability, but moderate scores for species sensitivity and hazard. The three wilayats identified as being at lowest overall risk from climate change impacts on the fisheries sector were all located in the Musandum (Khaṣab, Dibā al-Bay'ah, Bukhā), despite this being the warmest part of the Sultanate of Oman.

Table 4. Component metrics of the Climate Risk Assessment (CRA) for 30 coastal wilayats in the Sultanate of Oman. F = Fisheries Reliance, AC = Adaptive Capacity, S = Species Sensitivity, E = Fisheries Exposure, V= Socioeconomic Vulnerability, H = Meteorological Hazard.

Governorate	Official Name	F	AC (inverse)	S	E	V	H	RISK
SHAS	Ja'alan Banī Bū Ḥassan	1.00	0.73	0.36	0.62	1.00	0.60	0.64
DHOF	Ṣalālah	0.13	0.24	1.00	1.00	0.22	0.00	0.55
MUSC	Maṭraḥ [Muttrah]	0.15	0.00	0.70	0.00	0.20	0.88	0.44
AWUS	Al-Jāzer	0.11	0.43	0.22	0.87	0.13	0.45	0.42
SHAS	Ṣūr	0.07	0.67	0.36	0.62	0.07	0.60	0.41
SHAS	Maṣīrah [Masirah]	0.07	0.71	0.36	0.62	0.06	0.60	0.41
AWUS	Ad-Duqm	0.06	0.50	0.22	0.87	0.08	0.45	0.40
MUSC	Bawshar	0.19	0.04	0.45	0.05	0.23	0.88	0.40
AWUS	Maḥūt [Mahout]	0.05	0.49	0.22	0.87	0.06	0.45	0.40
SHAS	Ja'alan Banī Bū 'Alī	0.01	0.73	0.36	0.62	0.01	0.60	0.40
ABNS	Al-Khābūrah	0.39	0.73	0.00	0.11	0.42	1.00	0.38
MUSC	Masqaṭ [Muscat]	0.11	0.18	0.45	0.05	0.13	0.88	0.38
MUSC	As-Sīb [Seeb]	0.11	0.18	0.45	0.05	0.12	0.88	0.38
ABNS	As-Suwaīq	0.36	0.72	0.00	0.11	0.38	1.00	0.37
MUSC	Qurayyāt	0.05	0.29	0.45	0.05	0.06	0.88	0.36
ABNS	Ṣuḥār [Sohar]	0.23	0.62	0.00	0.11	0.24	1.00	0.34
ABNS	Al-Maṣna'ah [Musannah]	0.22	0.72	0.00	0.11	0.23	1.00	0.34
ABNS	Ṣaḥam	0.22	0.66	0.00	0.11	0.23	1.00	0.33
ABNS	Barka'	0.20	0.69	0.00	0.11	0.21	1.00	0.33
DHOF	Ṭāqah	0.16	0.30	0.79	0.31	0.18	0.00	0.32
ABNS	Liwa	0.15	0.68	0.00	0.11	0.16	1.00	0.32
ABNS	Shināṣ	0.14	0.68	0.00	0.11	0.14	1.00	0.31
DHOF	Sadaḥ	0.07	0.30	0.79	0.31	0.07	0.00	0.29
DHOF	Mirbāṭ	0.04	0.30	0.79	0.31	0.04	0.00	0.29
DHOF	Shalīm & Juzur al-Ḥallāniyyāt	0.04	0.29	0.79	0.31	0.04	0.00	0.28
DHOF	Ḍalkūt [Dhalkut]	0.03	0.30	0.79	0.31	0.03	0.00	0.28
DHOF	Rakhyūt	0.00	0.30	0.79	0.31	0.00	0.00	0.27
MUSA	Bukhā	0.07	1.00	0.39	0.06	0.10	0.45	0.25
MUSA	Dibā al-Bay'ah	0.05	0.97	0.39	0.06	0.08	0.45	0.24
MUSA	Khaṣab	0.02	0.96	0.39	0.06	0.03	0.45	0.23

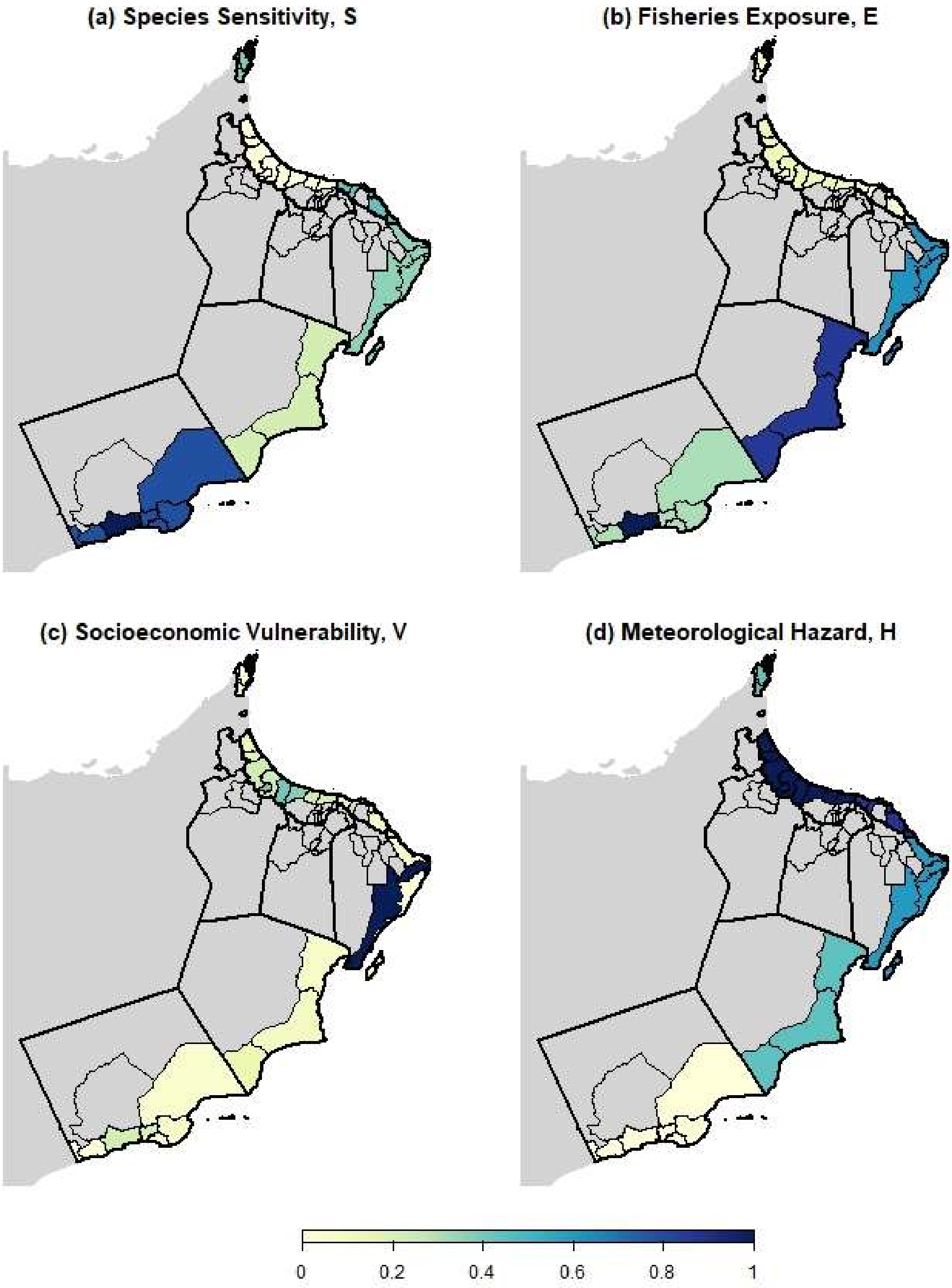

Figure 13. Thematic maps showing the spatial distribution of the four main component metrics of the Climate Risk Assessment (CRA) across the 30 coastal wilayats in the Sultanate of Oman. These metrics include: S = Species Sensitivity (map a), E = Fisheries Exposure (map b), V= Socioeconomic Vulnerability (map c), and H = Meteorological Hazard (map d). In each map, colour-shading indicates each wilayat's ranking (scaled from 0 to 1; see scale bar below the maps), where light yellow shading indicates low levels, and dark blue shading indicates high levels of sensitivity, exposure, vulnerability or hazard. Wilayats that lack coastal borders are shown in grey; thick border lines indicate the governorates. For the *overall climate risk* scores, based on the combination of S, E, V and H.

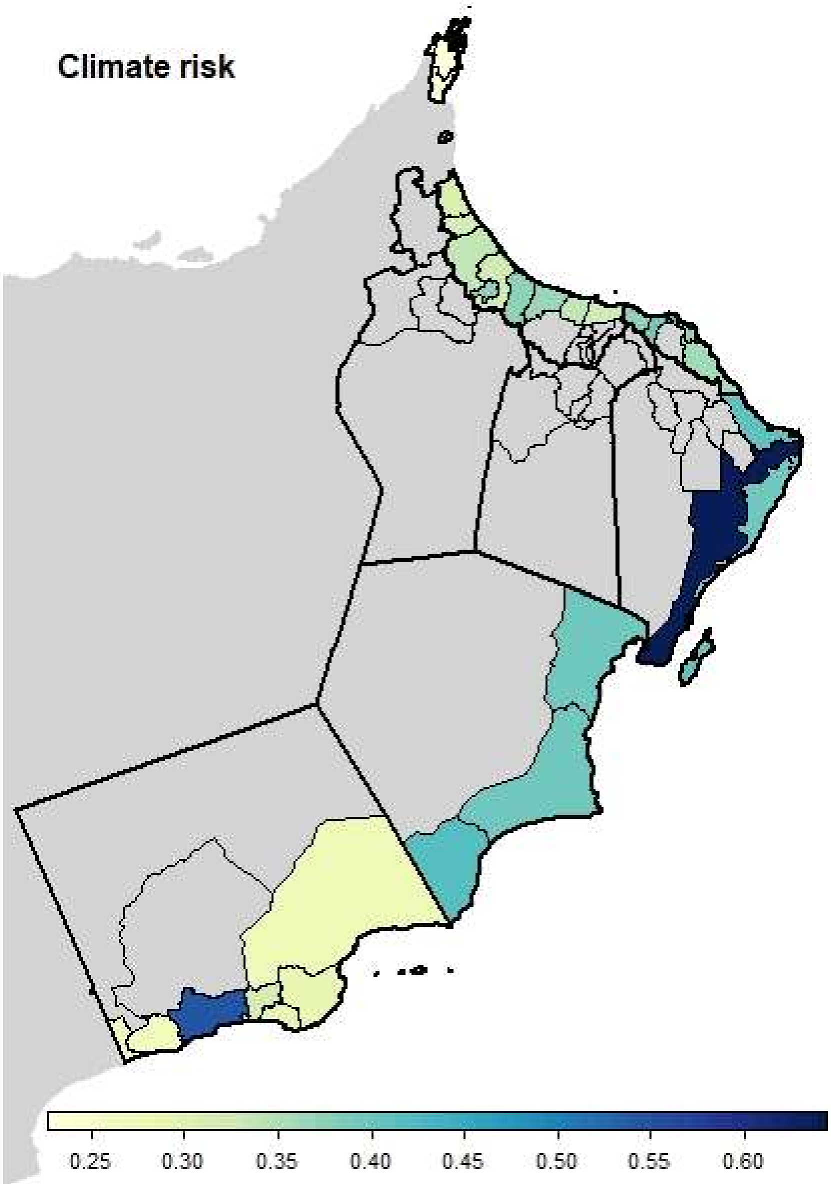

Figure 14. Thematic map showing the *Overall Climate Risk* scores for each the 30 coastal wilayats in the Sultanate of Oman, where yellow light shading indicates lower climate risk, and dark blue shading indicates higher risk (scaled from 0 to 1; see scale bar below the map). Wilayats that lack coastal borders are shown in grey; thick border lines indicate the governorates. The overall climate risk scores presented here are based on the unweighted means of the risk component metrics shown in the previous figure, i.e. as the average of Species Sensitivity (S), Fisheries Exposure (F), Socioeconomic Vulnerability (V) and Meteorological Hazard (H).

8 Aquaculture Assessment

So far, very few climate vulnerability analyses (CVAs) or climate risk assessments (CRAs) have been carried out that have specifically focussed on the aquaculture sector. Among the exceptions is that of Doubleday et al. (2013), who evaluated the relative risk levels that climate change poses to different types of aquaculture in south-eastern Australia, and who reported that species cultured from wild spat (such as rock oysters) were particularly at risk, as opposed to species where all stages of culture take place in fully controlled conditions. An analysis of climate-related vulnerability of aquaculture has also been carried out for various European countries, ranging from Norway and Finland in the north, to Mediterranean countries in the south (Kamermans et al., 2010) which showed that individual countries differed substantially in risk levels to their aquaculture sectors.

Here, we carry out a CRA for Oman's aquaculture sector, taking into account the country's aspirations to grow the industry rapidly to a regionally leading position (MAFW, 2019), both from a socio-economic perspective to generate revenue and enhance food security, but also to support the development of a skilled workforce of Omani nationals in the aquaculture sector. A growing body of research on Omani aquaculture exists (e.g. Al-Rashdi & Iwao 2008; Al-Rashdi et al. 2011, 2018), including on disease risk (Peeler & Scott 2018), the focus here is specifically on climate change-related risk factors, which are analysed separately for each of the important cultured species and separated by governorate.

8.1 Species included

Based on discussions between Cefas and the Ministry of Agriculture, Fisheries and Water Resources in context of strengthening biosecurity measures required to successfully and safely expand the aquaculture sector of Oman, Peeler & Scott (2018) compiled information on a portfolio of species that are considered key for aquaculture development in the near future. Based on Peeler & Scott (2018), and with supplementary information from Prins (2015), the important (marine) aquaculture species for Oman may be summarised as in Table 5.

Greatest aspiration levels are for shrimp (about 130,000 tonnes production, valued at OMR 320 million), sea breams (projected production 15,500 tonnes, OMR 55 million) and Atlantic salmon (projected production 20,000 tonnes, OMR 55 million). For groupers (9000 tonnes) and Oman abalone (2000 tonnes) the total projected production is less, but owing to the relatively high price per kg the total value of production is still high (estimated at OMR 64 million and OMR 9 million, respectively). It is of note that for only two of the above species – shrimps and sea breams – Oman has fairly extensive history of past production at commercial levels (while several of the other species have been produced commercially in very modest quantities, and only for short time periods).

The broad potential for development of Oman's aquaculture sector with respect to species, aquaculture systems and locations is summaries in Table 5.

Table 5. Key aquaculture species and projected production (based on Peeler & Scott 2018, with supplementary information for cobia taken from Prins 2016). Price per kg is expressed in 2018-US$ and based on mean global aquaculture price (from FAO fisheries and aquaculture statistics). Projected value by 2023 is based on projected production (Peeler & Scott 2018, Prins 2016) multiplied by standard US$ 2018 price/kg values. Unit prices are converted to total projected value based on a standard US$:OMR exchange rate of 2.6:1.. All projected data on production and value should only be seen as approximate and indicative of potential future development.

Species group	Species	Common name	Type of culture	Projected production	Price/kg	Projected value (OMR)	Regions
Sea breams	*Sparus aurata*	Gilthead sea bream	Marine cages; RAS	15500	$4.73	55,000,000	Musandam, Muscat, Ash Sharqiyah
	Sparidentex hasta = Acanthopagrus cuvieri	Sobaity sea bream			$13.25		Musandam, Muscat, Ash Sharqiyah
	Rhabdosargus sarba	Goldlined sea bream			$9.79		Musandam, Muscat, Ash Sharqiyah
Groupers	*Cephalopholis hemistiktos*	Yellowfin hind (grouper)	RAS	9000	$18.59	64,000,000	not specified
	Epinephelus tauvina	Greasy grouper			$18.59		not specified
Asian sea bass	*Lates calcarifer*	Asian seabass / Barramundi	Marine cages	2500	$4.52	4,350,000	not specified
Amberjacks	*Seriola quinqueradiata*	Japanese amberjack	Marine cages	2000	$7.77	7,550,000	Muscat, Ash Sharqiyah, Al Wusta
	Seriola dumerili	Greater amberjack			$9.10		Muscat, Ash Sharqiyah, Al Wusta
	Seriola lalandi	Yellowtail amberjack			$12.62		Muscat, Sharqiyah, Al Wusta
Cobia	*Rachycentron canadum*	Cobia	Marine cages		$2.83		not specified
Red snapper	*Lutjanus malabaricus*	Red snapper (Hamra)	Marine cages	100	$6.62	254,000	not specified
Pompano	*Trachinotus blochii*	Scubnose pompano	Marine cages	100	$4.77	184,000	not specified
Atlantic salmon	*Salmo salar*	Atlantic salmon	RAS	20000	$7.07	55,000,000	not specified
Shrimp	*Penaeus indicus*	Indian white prawn	Shrimp ponds	130000	$4.92	320,000,000	Ash Sharqiyah, Al Wusta
	Penaeus vannamei	Whiteleg shrimp			$6.09		Ash Sharqiyah, Al Wusta
	Penaeus monodon	Giant tiger prawn			$8.39		Ash Sharqiyah, Al Wusta
Abalone	*Haliotis mariae*	Oman abalone	RAS and restocking	2000	$11.30	9,000,000	Dhofar
Oyster	*Saccostrea cucullata*	Hooded or Rock oyster			$10.31		not specified
	Crassostrea rhizophorae	Mangrove cupped oyster			$1.00		not specified
Echinoderms	*Holothuria scabra*	Sand fish sea cucumber	Marine ponds and raceways restocking	2000	$5.27	4,060,000	Al Wusta

8.2 Sensitivity to thermal stress

For each of the above 20 target or candidate aquaculture species, data on the ‘maximum preferred temperature’ was compiled in the same way as in the fisheries sensitivity analysis. Specifically, the maximum preferred temperature (TP90) of a species is defined as the 90th percentile temperature (TP90), based on sea surface temperatures in the observed distribution range of the species in the wild, as recorded in Aquamaps. Thus, for a given species’ wild population, it may be assumed that 90% of individuals occur in areas that have sea temperatures below the TP90 temperature value. The values of TP90 for all species are shown in Table 6. TP90 ranged between 12.77°C in Atlantic salmon, and 29.77°C in the grouper species, yellowfin hind; averaged across all species, TP90 was 27.38°C.

We then combined each species’ TP90 value with the mean sea surface temperature for each of Oman’s 7 coastal governorates, to calculate the ‘thermal safety margin’ (TSM) for that species within each governorate, as the difference between TP90 and coastal SST. A positive value of TSM (shaded blue in Table 6) implies that the species’ maximum preferred temperature is higher than the mean annual SST in the region, and hence that the species is unlikely to suffer from thermal stress if held under ambient temperature conditions. By contrast a negative value of TSM (shaded red in table 6) implies that the species maximum preferred temperature is lower than the mean annual SST in the region, and therefore that the region’s ambient temperature are beyond the species’ optimal thermal tolerance ranges; if held under ambient conditions, these species are likely to be at risk of thermal stress in the region, in particular during the warmer season(s) of the year.

Atlantic salmon, in particular, stands out in Table 6 as having a very low maximum preferred temperature (12.77°C) however the plans are to grow salmon in fully enclosed refrigerated RAS systems. In Oman, this temperate-water species would not thrive if held in ambient conditions as would be the case with sea cages, which is how salmon are typically cultured in most temperate countries. In the specific case of salmon where fully temperature-controlled RAS are planned, this risk factor is not included in further analysis of climate risk.

Table 6. Risk from *thermal stress*. The 'maximum preferred temperatures' (TP90) for 20 target or candidate aquaculture species in Oman, as well as – shown separately for each governorate – the 'thermal safety margins' for each of these species. The thermal safety margins are colour-coded from dark blue (low risk) to red (high risk). At the bottom of the table, the annual mean sea surface temperatures (SST) for coastal waters adjacent to each governorate are indicated. See text for full interpretation. *Note:* for Atlantic salmon, which in Oman is planned to be cultured in fully temperature-controlled RAS conditions, values of TSM are shown but no risk-based colour-shading was applied.

				Species' thermal safety margin (TSM) by governorate (°C)					
Species group	**Species**	**Common name**	**TP90 (°C)**	**Musan-dam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Sea breams	*Sparus aurata*	Gilthead sea bream	21.44	***-7.42***	-7.31	***-7.18***	***-5.66***	-4.96	-5.57
	Sparidentex hasta	Sobaity sea bream	28.24	***-0.62***	-0.51	***-0.38***	***1.14***	1.84	1.23
	Rhabdosargus sarba	Goldlined sea bream	28.43	***-0.43***	-0.32	***-0.19***	***1.33***	2.03	1.42
Groupers	*Cephalopholis hemistiktos*	Yellowfin hind (grouper)	29.77	0.91	1.02	1.15	2.67	3.37	2.76
	Epinephelus tauvina	Greasy grouper	29.15	0.29	0.40	0.53	2.05	2.75	2.14
Asian sea bass	*Lates calcarifer*	Asian seabass / Barramundi	28.89	0.03	0.14	0.27	1.79	2.49	1.88
Amber-jacks	*Seriola quinqueradiata*	Japanese amberjack	24.73	-4.13	-4.02	***-3.89***	***-2.37***	***-1.67***	-2.28
	Seriola dumerili	Greater amberjack	28.23	-0.63	-0.52	***-0.39***	***1.13***	***1.83***	1.22
	Seriola lalandi	Yellowtail amberjack	27.79	-1.07	-0.96	***-0.83***	***0.69***	***1.39***	0.78
Cobia	*Rachycentron canadum*	Cobia	28.77	-0.09	0.02	0.15	1.67	2.37	1.76
Red snapper	*Lutjanus malabaricus*	Red snapper (Hamra)	28.84	-0.02	0.09	0.22	1.74	2.44	1.83
Pompano	*Trachinotus blochii*	Scubnose pompano	29.12	0.26	0.37	0.50	2.02	2.72	2.11
Atlantic salmon	*Salmo salar*	Atlantic salmon	12.77	(-16.09)	(-15.98)	(-15.85)	(-14.33)	(-13.63)	(-14.24)
Shrimp	*Penaeus indicus*	Indian white prawn	29.18	0.32	0.43	0.56	***2.08***	***2.78***	2.17
	Penaeus vannamei	Whiteleg shrimp	29.08	0.22	0.33	0.46	***1.98***	***2.68***	2.07
	Penaeus monodon	Giant tiger prawn	29.10	0.24	0.35	0.48	***2.00***	***2.70***	2.09
Abalone	*Haliotis mariae*	Oman Abalone	27.50	-1.36	-1.25	-1.12	0.40	1.10	***0.49***
Oyster	*Saccostrea cucullata*	Hooded or Rock oyster	29.12	0.26	0.37	0.50	2.02	2.72	2.11
	Crassostrea rhizophorae	Mangrove cupped oyster	28.19	-0.67	-0.56	-0.43	1.09	1.79	1.18
Echino-derms	*Holothuria scabra*	Sand fish sea cucumber	29.27	0.41	0.52	0.65	2.17	***2.87***	2.26
Annual mean SST by governorate (°C)				**28.86**	**28.75**	**28.62**	**27.10**	**26.40**	**27.01**

Gilthead seabream (TP90 = 21.44°C) is found to have negative thermal safety margins in each of Oman's coastal governorates, indicating risk from thermal stress, in particular in the northern governorates. In spite of these results indicating thermally stressful conditions for gilthead seabream which is not endemic to Oman but originates from the Mediterranean and North-east Atlantic, this species is cultured commercially in marine sea cages in Quryiat, with further developments scheduled for Musandam, Muscat, and Ash Sharqiyah South governorates (Table 5). Aquaculture studies have reported tolerance to seawater temperatures of 10–33°C (Al-Rashdi et al., 2011); this is well beyond the typical natural thermal ranges for gilthead seabream. By contrast, two related cultured seabream species that are indigenous to Omani waters – sobaity seabream and goldlined seabream – show thermal safety margins that may be considered in line with ambient conditions for Oman (especially in Ash Sharqiyah South, and further south), indicating lower risk of thermal stress for these species if held in marine cage culture.

There was no evidence for risk of thermal stress to barramundi, cobia, red snapper or pompano if held in marine cage culture. Of the three amberjack species being considered, two species – yellowtail and greater amberjack – are found to be at low risk from thermal stress owing to thermal safety margins that are either positive or close to zero. However, one of the amberjack species considered – Japanese amberjack *Seriola quinqueradiata* – is found here to be at fairly high risk of thermal stress if held in ambient temperature marine cages.

While yellowfin hind and greasy grouper would be held in controlled RAS systems and therefore would be less exposed to ambient temperature conditions than fish species held in sea pens, both these species appear to be within natural temperature conditions in Omani waters.

Each of the three shrimp species in Omani aquaculture have high TP90 values (above 29°C) and correspondingly, positive thermal safety margins for each of the governorates indicating low risk of thermal stress; this was particularly so for Ash Sharqiyah South and Al Wusta, the governorates where these are produced.

For Oman abalone *Haliotis mariae*, ambient conditions in Dhofar (where currently cultured) are in agreement with the species' thermal preferences. For sand fish sea cucumber, ambient conditions in Al Wusta (where production takes place) are in agreement with the species' thermal preferences.

It should be noted that we calculated the 'thermal safety margin' (TSM) for species assuming the annual mean sea surface temperature (SST) and not the yearly maximum. As illustrated in figure 7, these values can differ considerably. For example, the annual mean temperature for Musandam Governorate is around 28.7°C but the yearly maximum may exceed 33°C and hence our assessment of thermal sensitivity may be somewhat conservative (i.e. an under-estimate)

8.3 Exposure to flooding and storm surge

For each combination of aquaculture species and governorate, a relative measure of exposure to coastal flooding and storm surge was calculated, associated with sea level rise and tropical cyclones (see Table 7). Firstly, for each species, a *sensitivity score to flooding and storm surge* was defined as either 1 (low), 2 (medium) or 3 (high), based on the type of culture and species biological characteristics. Species typically reared in floating sea cages, such as sea breams, were scored as having 'low' sensitivity as these facilities are not directly impacted by flooding or coastal inundation however land-based infrastructure can be affected by coastal flooding. By contrast species cultured in shrimp ponds or raceways (such as sea cucumbers), often located in flat-laying terrain close to the sea and highly prone to inundation and were scored as having 'high' sensitivity, whereas other species reared in RAS were scored as having intermediate sensitivity as they are typically connected with coastal areas. For each of Oman's coastal governorates, a *flooding hazard score* was calculated, based on the area (per km of coastline) predicted to be flooded if mean sea level rises by 0.2 m; this was based on a recent study by Al-Buloshi et al. (2014) who simulated the impacts of climate change-related sea level rise and coastal flooding on Oman. For each species, *relative risk from flooding and storm surge* per governorate was then calculated as *sensitivity* x *hazard*. In Table 7, we have used colour-shading to emphasise in which governorate, particular species are likely to be more exposed to risk from flooding and storm surge.

Table 7. Relative exposure to *flooding and storm surge*, estimated for each of Oman's key aquaculture species and separately by governorate. For each aquaculture species, a *sensitivity* score to flooding is shown (third column), ranked 1 (low) to 3 (high), based on the type of culture and species biological characteristics. For each coastal governorate, a *flooding hazard* score is shown based on the area predicted to be flooded if mean sea level rises by 0.2 m (from Al-Buloshi et al., 2014) per km of coastline. *Relative risk* per species and governorate is then calculated as *sensitivity* x *hazard*. Colour-shading indicates low risk (light) to high risk (dark red). See text for full interpretation.

			Species' relative hazard by governorate					
Species	**Common name**	**Sensitivity to sea level rise**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Sparus aurata	Gilthead sea bream	1	***0.07***	0.25	***0.26***	***0.25***	0.18	0.05
Sparidentex hasta	Sobaity sea bream	1	***0.07***	0.25	***0.26***	***0.25***	0.18	0.05
Rhabdosargus sarba	Goldlined sea bream	1	***0.07***	0.25	***0.26***	***0.25***	0.18	0.05
Cephalopholis hemistiktos	Yellowfin hind	2	0.14	0.50	0.51	0.50	0.36	0.10
Epinephelus tauvina	Greasy grouper	2	0.14	0.50	0.51	0.50	0.36	0.10
Lates calcarifer	Asian seabass	1	0.07	0.25	0.26	0.25	0.18	0.05
Seriola quinqueradiata	Japanese amberjack	1	0.07	0.25	***0.26***	***0.25***	***0.18***	0.05
Seriola dumerili	Greater amberjack	1	0.07	0.25	***0.26***	***0.25***	***0.18***	0.05
Seriola lalandi	Yellowtail amberjack	1	0.07	0.25	***0.26***	***0.25***	***0.18***	0.05
Rachycentron canadum	Cobia	1	0.07	0.25	0.26	0.25	0.18	0.05
Lutjanus malabaricus	Red snapper	1	0.07	0.25	0.26	0.25	0.18	0.05
Trachinotus blochii	Scubnose pompano	1	0.07	0.25	0.26	0.25	0.18	0.05
Salmo salar	Atlantic salmon	2	0.14	0.50	0.51	0.50	0.36	0.10
Penaeus indicus	Indian white prawn	3	0.21	0.75	0.77	***0.75***	***0.54***	0.14
Penaeus vannamei	Whiteleg shrimp	3	0.21	0.75	0.77	***0.75***	***0.54***	0.14
Penaeus monodon	Giant tiger prawn	3	0.21	0.75	0.77	***0.75***	***0.54***	0.14
Haliotis mariae	Oman Abalone	2	0.14	0.50	0.51	0.50	0.36	***0.10***
Saccostrea cucullata	Hooded oyster	1	0.07	0.25	0.26	0.25	0.18	0.05
Crassostrea rhizophorae	Cupped oyster	1	0.07	0.25	0.26	0.25	0.18	0.05
Holothuria scabra	Sea cucumber	3	0.21	0.75	0.77	0.75	***0.54***	0.14
Inundated area (km²) with sea level rise 0.2 m			35	60	50	120	105	25
Coastline (km)			495	241	196	480	584	523
Flooding hazard: inundated area (km²) per km of coastline with sea level rise 0.2 m			0.07	0.25	0.26	0.25	0.18	0.05

Shrimp culture, in particular, is suggested to be at higher risk from sea level rise and coastal flooding, in particular in Ash Sharqiyah and Muscat. The exposure scores reported here for shrimp are lower for Al Wusta, but it is of note that within this governorate, suitable locations for shrimp ponds would likely be located in low-lying areas and hence be more prone to flooding. This risk factor was particularly low for typically sea cage-farmed species (sea breams, amberjacks, Asian sea bass), and for the governorate of Musandam; the highly irregular coastline of this governorate with many sheltered bays appear to render Oman's northernmost governorate least susceptible to losses from this hazard.

8.4 Hazard from low-oxygen levels

Given Oman's proximity to the world's largest, naturally occurring marine low-oxygen zone (review: Acharya & Panigrahi, 2016), the potential for low oxygen levels in seawater to impact aquaculture is seen here as an important risk factor to the sector. In particular, there is evidence of an increasing prevalence of low-oxygen conditions in the Arabian Sea since the 1970s (Piontkovski & Al-Oufi 2015; Piontkovski & Queste, 2016; Queste et al., 2018), a trend expected to continue into the future with warming sea conditions.

Table 8. Relative hazard from *low-oxygen levels in seawater*, estimated for each of Oman's key aquaculture species and separately by governorate. For each aquaculture species, a *sensitivity* score low oxygen risk is shown (third column), ranked 1 (low) to 3 (high), based on the type of culture and species biological characteristics. For each coastal governorate, a *low oxygen hazard* score (ranked 1, low to 4 high) is shown based geographical patterns in the duration and intensity of low oxygen conditions linked to the Arabian Sea oxygen minimum zone (based on Acharya & Panigrahi, 2016; Piontkovski & Queste, 2016; Queste et al., 2018). *Relative risk* per species and governorate is then calculated as *sensitivity* x *hazard*. Colour-shading indicates low risk (light) to high risk (dark red). See text for full interpretation.

			Species' relative hazard by governorate (1 lowest, 12 highest)					
Species	**Common name**	**Sensitivity to low oxygen risk**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Sparus aurata	Gilthead sea bream	3	***3***	3	***6***	***9***	12	12
Sparidentex hasta	Sobaity sea bream	3	***3***	3	***6***	***9***	12	12
Rhabdosargus sarba	Goldlined sea bream	3	***3***	3	***6***	***9***	12	12
Cephalopholis hemistiktos	Yellowfin hind	1	1	1	2	3	4	4
Epinephelus tauvina	Greasy grouper	1	1	1	2	3	4	4
Lates calcarifer	Asian seabass	3	3	3	6	9	12	12
Seriola quinqueradiata	Japanese amberjack	3	3	3	***6***	***9***	***12***	12
Seriola dumerili	Greater amberjack	3	3	3	***6***	***9***	***12***	12
Seriola lalandi	Yellowtail amberjack	3	3	3	***6***	***9***	***12***	12
Rachycentron canadum	Cobia	3	3	3	6	9	12	12
Lutjanus malabaricus	Red snapper	3	3	3	6	9	12	12
Trachinotus blochii	Scubnose pompano	3	3	3	6	9	12	12
Salmo salar	Atlantic salmon	2	2	2	4	6	8	8
Penaeus indicus	Indian white prawn	1	1	1	2	***3***	***4***	4
Penaeus vannamei	Whiteleg shrimp	1	1	1	2	***3***	***4***	4
Penaeus monodon	Giant tiger prawn	1	1	1	2	***3***	***4***	4
Haliotis mariae	Oman Abalone	2	2	2	4	6	8	***8***
Saccostrea cucullata	Hooded oyster	1	1	1	2	3	4	4
Crassostrea rhizophorae	Cupped oyster	1	1	1	2	3	4	4
Holothuria scabra	Sea cucumber	2	2	2	4	6	***8***	8
Low-oxygen hazard by governorate (1 low, 4 high)			1	1	2	3	4	4

For each aquaculture species and governorate, an assessment of relative hazard from low-oxygen levels in seawater is provided in table 8. Firstly, major spatial differences within Oman in the extent to which governorates are exposed to this hazard should be noted. In southern governorates coastal ecosystems are subject to extensive seasonal upwelling during the summer monsoon (June-September) which may be accompanied by substantial drops in oxygen levels (referred to as hypoxia). The likelihood of such hypoxic conditions is lower further north (such as in Ash Sharqiyah) and low-oxygen conditions are rare (albeit not fully absent) in the northernmost governorates. In our climate risk analysis, these spatial differences are reflected in 'low-oxygen hazard scores' ranging from 4 (highest) in Dhofar and Al Wusta, to 1 (lowest) in Musandam and Al Batinah.

Secondly, species sensitivity to low oxygen conditions varies and is generally highest in faster-swimming fish species such as sea bream and sea bass (sensitivity score 3; Table 7), whereas sessile species such as oysters have lower oxygen requirements (sensitivity score 1). Furthermore, the type of culture is also of relevance and was here included in 'species sensitivity'; fish held under fully controlled RAS conditions (e.g. groupers) are unlikely to be impacted, especially if spatially separated from the sea (sensitivity score 1), whereas species held in sea cages are directly impacted by low-oxygen seawater and may suffer extensive mortalities. Species where re-stocking take place (abalone, sand fish sea cucumber) are considered to have intermediate sensitivity (sensitivity score 2), and likewise salmon, which although planned to be held in RAS, are active-swimming fish and have high oxygen requirements.

In combination, species' relative hazard scores from low-oxygen by governorate was predicted to be greatest (risk score 12, on a scale of 1-12) for cage-produced fish species if produced in Al Wusta or Dhofar (sea breams, amberjacks, seabass, cobia), noting that most production for these species is envisaged further north where this risk factor is lower. Low-oxygen risk is predicted to be intermediate (score 8) for abalone and sea cucumber in Dhofar and Al Wusta and would potentially impact these after restocking.

8.5 Vulnerability to disease

Globally, the risk from diseases to aquaculture is one of the primary drivers of successes or losses, with the FAO estimating that at least US$ 6 billion is lost annually from aquaculture yield (Jennings et al. 2016). Certain diseases play a particularly dominant role; for example, white spot disease in shrimp has continued to cause losses exceeding $1 billion per annum since its emergence in the 1990s (Stentiford et al. 2012). Emergent issues include microsporidiosis in farmed sea bream, which have the ability to stunt fish development, with limited scope for treatment (Palenzuela et al. 2014). Also in Oman, stability and growth of aquaculture production are at risk owing to these and other pathogens. Disease risk is incorporated into this climate risk assessment as disease risk may increase due to two factors as a result of climate change. Firstly, in a warming world the geographic distribution of diseases in the wild – and hence available to infect farmed species – may change and farmed species may be exposed to new diseases. Secondly if animals become thermally stressed within an aquaculture facility they may become immuncocompromised and more susceptible to disease.

Our analysis builds upon the report by Peeler & Scott (2018) describing their collaborative work under the UK Gulf Marine Environment Partnership (UK-GMEP) Programme which was aimed at developing aquatic animal health legislation for Oman. We have used their revised list of fish, molluscan and crustacean diseases recommended surveillance and listing in national legislation (Table 3 in Peeler & Scott 2018). Their list combines information on the expected level of production of aquaculture species in Oman, with information on aquatic animal diseases per species as listed by the World Organisation for Animal Health (OIE, formerly Office International des Epizooties).

In the present analysis, proxies for overall disease-related risk for Oman aquaculture species were calculated as the average of three separate factors. These included, firstly, the total number of OIE listed aquatic diseases per species (Peeler & Scott 2018), including viral, bacterial and fungal diseases; we regard this as a useful indicator given the stature of the OIE, but caution against its over-interpretation as it does not account for diseases not listed, and aquaculture species intensively farmed globally, and hence more thoroughly researched might be over-represented. Nevertheless, its inclusion is warranted on pragmatic grounds.

The second disease risk factor relates to the origin of broodstock, and is ranked 1 if all aquaculture stock is derived from local broodstock (and hence the risk of pathogen import is low); as 2 if partly derived from local, partly from imported broodstock; and as 3 if fully derived from imported broodstock (and hence the risk of pathogen import is high). The third risk factor is based on concentration of production, where having multiple, spatially separated farms as opposed to a single farm is seen as a means to reduce risk – in an unfortunate, potential scenario where a farm may have been infected – impacting nation-wide production of a species., i.e. having only local impact once mitigation is in place. This risk factor was also ranked 1-3 (1, production spread over at least 5 farms, hence low risk; 2, production in 2-4 farms, hence medium risk; 3, concentrated in 1 farm only, hence high risk).

Combined, overall disease risk ranked highest in shrimp culture, reflective of a large number (9) of OIE listed diseases for *Penaeus vannamei* and *P. monodon*, two relatively fast-growing, fecund species that are widely cultivated across southern Asia. For the local, endemic species *P. indicus* only 1 disease type is listed, but this might reflect that it has been researched much less intensively than the two other, widely cultivated species. In particular, *P. indicus* is listed as being susceptible to white spot disease – by far the most important shrimp disease in southern Asia. In the case of shrimp pond culture, where brackish seawater is brought in, it is difficult to fully exclude ponds from disease; barriers or filters can be incorporated but it remains challenging to fully exclude disease vectors (Peeler & Scott 2018).

For amberjacks the import of live fish is envisaged to provide broodstock, and some import of juveniles for grouper culture, which would increase risk of pathogen introduction. Likewise continued import of shrimp broodstock may be required (Peeler & Scott 2018); in each of these cases close screening for pathogens has been recommended.

In the case of Atlantic salmon, a single RAS facility is expected to come into production in the next 5 years; provided original stock is sourced from a source free of OIE listed diseases, disease risk is likely low even though many diseases have been OIE listed for salmon in colder climates. As Oman does not have endemic salmonid populations there is no risk of disease risk spread from wild populations. Moreover, disease spread from RAS is inherently low (Peeler & Scott 2018). However this situation could change if salmon production would expand beyond a few, isolated RAS sites.

We emphasise that interpretation of our disease risk factors requires caution, as many other potential factors could not be included here; importantly, these include the severity by which a single type of pathogen may impact stock (which may range from a moderate reduction in growth, to mass mortalities in multiple farms) and the speed by which pathogens may spread both within and across farms.

Table 9. Proxies for vulnerability to *disease-related risks* for Oman aquaculture species (*right-most column*), calculated as the average of three risk factors: (a) the total number of OIE listed diseases per species as reported in Peeler & Scott (2018); (b) origin of broodstock, whether locally produced or imported; and (c) concentration of production, in few or many farms. *Number of OIE listed diseases* combines the viral, bacterial and fungal diseases listed in the table's central columns. *Broodstock-related risk* is ranked as follows: 1, all stock derived from local broodstock (low risk of pathogen import); 2, stock derived partly from local, partly from imported broodstock (medium risk); 3, fully derived from imported broodstock (high risk of pathogen import). *Concentration of production* is ranked 1-3, as follows: 1, production spread over at least 5 farms (risk spread, hence lower); 2, production in 2-4 farms; 3, production in 1 farm only (risk concentrated, hence higher). Colour-shading indicates low risk (light) to high risk (dark red). See text for full interpretation. *Note:* interpretation of our disease risk factors requires caution, as many other potential factors could not be included here; importantly, these include the severity of impact from a single pathogen, and the speed by which particular pathogens may spread.

			Viral													***Bacterial***			***Fungal***			
Species	**Common name**	**Number of OIE listed diseases**	Epizootic ulcerative syndrome	Grouper iridoviral disease	Megalocytivirus	Red sea bream iridoviral disease	Viral encephalopathy and retinopathy	Infectious hypodermal, haematopoietic necrosis	Infectious myonecrosis virus	Taura syndrome virus	Viral covert mortality disease of shrimps	White spot disease	Yellow head virus	Abalone herpesvirus	Abalone shrivelling syndrome associated	Acute hepatopancreas necrosis	Necrotising hepatopancreatitis	Xenohaliotis californiensis	Hepatopancreatic microsporidiosis caused by Enterocytozoon	**Local produce or import of brood-stock**	**Concen-tration of produc-tion**	***Overall vulnera bility to disease***
Sparus aurata	Gilthead sea bream	1					1													1	1	**1.0**
Sparidentex hasta	Sobaity sea bream	0																		1	1	**0.7**
Rhabdosargus sarba	Goldlined sea bream	1			1															1	1	**1.0**
Cephalopholis hemistiktos	Yellowfin hind	0																		2	2	**1.3**
Epinephelus tauvina	Greasy grouper	3		1		1	1													2	2	**2.3**
Lates calcarifer	Asian seabass	3	1			1	1													1	2	**2.0**
Seriola quinqueradiata	Japanese amberjack	2				1	1													3	2	**2.3**
Seriola dumerili	Greater amberjack	2				1	1													3	2	**2.3**
Seriola lalandi	Yellowtail amberjack	2				1	1													3	2	**2.3**
Rachycentron canadum	Cobia	0																			n.a.	**n.a.**
Lutjanus malabaricus	Red snapper	0																		1	3	**1.3**
Trachinotus blochii	Scubnose pompano	0																		1	3	**1.3**
Salmo salar	Atlantic salmon	0 *)																		1	3	**2.0**
Penaeus indicus	Indian white prawn	1										1								2	1	**1.3**
Penaeus vannamei	Whiteleg shrimp	9						1	1	1	1	1	1			1	1		1	2	1	**4.0**
Penaeus monodon	Giant tiger prawn	9						1	1	1	1	1	1			1	1		1	2	1	**4.0**
Haliotis mariae	Oman Abalone	3												1	1			1		1	1	**1.7**
Saccostrea cucullata	Hooded oyster	0																			n.a.	**n.a.**
Crassostrea rhizophorae	Cupped oyster	0																			n.a.	**n.a.**
Holothuria scabra	Sea cucumber	0																		1	2	**1.0**

8.6 Overall climate risk to aquaculture

Our assessment of *overall climate risk* to aquaculture in Oman combines four components of risk – (1) thermal sensitivity, (2) exposure to flooding and storm surge, (3) hazard from low-oxygen levels, and (4) vulnerability to disease each assess for each species and governorate. As shown in Table 10, information for thermal sensitivity, exposure to flooding, and hazard from low-oxygen levels is spatially disaggregated by governorate; in the case of overall disease risk, a single risk metric across all governorates is available per species.

Following the method applied for the fisheries climate risk analysis each of the four risk metrices was re-scaled between 0 and 1, where 0 implies lowest risk and 1 implies highest risk. Following re-scaling, the *overall climate risk* (per species, per governorate) is then calculated **as the unweighted mean of the four components**.

Overall climate risk is highest for shrimp culture, owing to (1) a high risk of disease prevalence, and (2) high exposure to flooding or storm surge. The latter relates to shrimp pond culture typically being located in low-lying terrain, close to the sea to allow intake of brackish water. The exposure to storm surge and flooding is relatively high in Ash Sharqiyah where shrimp culture is being started; this risk is lower on average for Al Wusta but within this governorate sites suitable to shrimp culture will typically be at low elevation and flood risk will depend on the exact location of each facility. For one of the three shrimp species, the endemic Indian white shrimp *Penaeus indicus*, the overall risk score is lower than for both other species *P. vannamei* and *P. monodon*; this is largely linked to the smaller number of OIE listed diseases for *P. indicus*, however as highlighted in the previous section, diseases in both other species have been investigated far more extensively which might reflect their disease listing, and *P. indicus* is impacted by the important white spot disease. This might mean a smaller difference in overall climate risk between the three shrimp species.

Overall climate risk was also found to be high in amberjacks, which is partly explained by their culture in sea cages which implies exposure to (1) pathogens (with amberjacks being at risk from at least two OIE listed viral diseases) and (2) potential hazard presented by low-oxygen levels in seawater (with amberjacks being active swimmers having relatively high oxygen demands). The risk from low-oxygen levels is relatively higher in waters off Al Wusta, which during the monsoon season are impacted by the Arabian Sea oxygen minimum zone. However, the exposure to flooding or storm surge on amberjacks is lower. It is of note that one of the three amberjack species examined – Japanese amberjack – is adapted to cooler water temperatures (lower maximum preferred temperature) than both others, and would therefore be subject to greater thermal stress if reared in sea cage conditions in Omani waters.

Low climate risk was recorded for aquaculture production of the two grouper species, yellowfin hind and greasy grouper. This has been proposed for RAS systems, which are inherently less impacted by ambient temperature or other environmental conditions – noting that groupers generally do not fare well in sea cages (and that RAS systems are mainly profitable if price per kg is high, as in groupers). Even so, both yellowfin hind and greasy grouper are well within their natural temperature ranges in Omani waters, and hence would experience little thermal stress if re-located outside. Moreover the fully isolated, RAS conditions also make exposure to pathogens less likely.

Table 10. Overall risks to aquaculture in Oman, as determined by the 4 components metrics (thermal sensitivity, exposure to flooding and storm surge, Hazard from low oxygen levels in seawater, disease vulnerability).

		Thermal sensitivity						*Exposure to flooding and storm surge*						*Hazard from low-oxygen levels in seawater*						*Disease Vulnerability*	***Overall climate risk***					
Species	**Common name**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**	**All governorates**	**Musandam**	**Al Batinah**	**Muscat**	**Ash Sharqiyah**	**Al Wusta**	**Dhofar**
Sparus aurata	Gilthead sea bream	***1.00***	0.99	***0.98***	***0.84***	0.77	0.83	***0.03***	0.28	***0.29***	***0.28***	0.18	0.00	***0.18***	0.18	***0.45***	***0.73***	1.00	1.00	0.10	***0.33***	0.39	***0.46***	***0.49***	0.51	0.48
Sparidentex hasta	Sobaity sea bream	***0.37***	0.36	***0.35***	***0.21***	0.14	0.20	***0.03***	0.28	***0.29***	***0.28***	0.18	0.00	***0.18***	0.18	***0.45***	***0.73***	1.00	1.00	0.00	***0.15***	0.21	***0.27***	***0.30***	0.33	0.30
Rhabdosargus sarba	Goldlined sea bream	***0.35***	0.34	***0.33***	***0.19***	0.12	0.18	***0.03***	0.28	***0.29***	***0.28***	0.18	0.00	***0.18***	0.18	***0.45***	***0.73***	1.00	1.00	0.10	***0.17***	0.23	***0.29***	***0.32***	0.35	0.32
C. hemistiktos	Yellowfin hind	0.23	0.22	0.21	0.06	0.00	0.06	0.13	0.63	0.64	0.63	0.43	0.07	0.00	0.00	0.09	0.18	0.27	0.27	0.20	0.14	0.26	0.29	0.27	0.23	0.15
Epinephelus tauvina	Greasy grouper	0.29	0.28	0.26	0.12	0.06	0.11	0.13	0.63	0.64	0.63	0.43	0.07	0.00	0.00	0.09	0.18	0.27	0.27	0.50	0.23	0.35	0.37	0.36	0.32	0.24
Lates calcarifer	Asian seabass	0.31	0.30	0.29	0.15	0.08	0.14	0.03	0.28	0.29	0.28	0.18	0.00	0.18	0.18	0.45	0.73	1.00	1.00	0.40	0.23	0.29	0.36	0.39	0.42	0.38
S. quinqueradiata	Japanese amberjack	0.70	0.68	***0.67***	***0.53***	***0.47***	0.52	0.03	0.28	***0.29***	***0.28***	***0.18***	0.00	0.18	0.18	***0.45***	***0.73***	***1.00***	1.00	0.50	0.35	0.41	***0.48***	***0.51***	***0.54***	0.51
Seriola dumerili	Greater amberjack	0.37	0.36	***0.35***	***0.21***	***0.14***	0.20	0.03	0.28	***0.29***	***0.28***	***0.18***	0.00	0.18	0.18	***0.45***	***0.73***	***1.00***	1.00	0.50	0.27	0.33	***0.40***	***0.43***	***0.46***	0.42
Seriola lalandi	Yellowtail amberjack	0.41	0.40	***0.39***	***0.25***	***0.18***	0.24	0.03	0.28	***0.29***	***0.28***	***0.18***	0.00	0.18	0.18	***0.45***	***0.73***	***1.00***	1.00	0.50	0.28	0.34	***0.41***	***0.44***	***0.47***	0.44
R. canadum	Cobia	0.32	0.31	0.30	0.16	0.09	0.15	0.03	0.28	0.29	0.28	0.18	0.00	0.18	0.18	0.45	0.73	1.00	1.00	0.50	0.26	0.32	0.39	0.42	0.44	0.41
Lutjanus malabaricus	Red snapper	0.31	0.30	0.29	0.15	0.09	0.14	0.03	0.28	0.29	0.28	0.18	0.00	0.18	0.18	0.45	0.73	1.00	1.00	0.20	0.18	0.24	0.31	0.34	0.37	0.34
Trachinotus blochii	Scubnose pompano	0.29	0.28	0.27	0.13	0.06	0.12	0.03	0.28	0.29	0.28	0.18	0.00	0.18	0.18	0.45	0.73	1.00	1.00	0.20	0.18	0.24	0.30	0.33	0.36	0.33
Salmo salar	Atlantic salmon	0.50	0.50	0.50	0.50	0.50	0.50	0.13	0.63	0.64	0.63	0.43	0.07	0.09	0.09	0.27	0.45	0.64	0.64	0.40	0.28	0.40	0.45	0.50	0.49	0.40
Penaeus indicus	Indian white prawn	0.28	0.27	0.26	***0.12***	***0.05***	0.11	0.23	0.97	1.00	***0.98***	***0.69***	0.13	0.00	0.00	0.09	***0.18***	***0.27***	0.27	0.20	0.18	0.36	0.39	***0.37***	***0.30***	0.18
Penaeus vannamei	Whiteleg shrimp	0.29	0.28	0.27	***0.13***	***0.06***	0.12	0.23	0.97	1.00	***0.98***	***0.69***	0.13	0.00	0.00	0.09	***0.18***	***0.27***	0.27	1.00	0.38	0.56	0.59	***0.57***	***0.51***	0.38
Penaeus monodon	Giant tiger prawn	0.29	0.28	0.27	***0.13***	***0.06***	0.12	0.23	0.97	1.00	***0.98***	***0.69***	0.13	0.00	0.00	0.09	***0.18***	***0.27***	0.27	1.00	0.38	0.56	0.59	***0.57***	***0.50***	0.38
Haliotis mariae	Oman Abalone	0.44	0.43	0.42	0.28	0.21	***0.27***	0.13	0.63	0.64	0.63	0.43	***0.07***	0.09	0.09	0.27	0.45	0.64	***0.64***	0.30	0.24	0.36	0.41	0.42	0.40	***0.32***
Saccostrea cucullata	Hooded oyster	0.29	0.28	0.27	0.13	0.06	0.12	0.03	0.28	0.29	0.28	0.18	0.00	0.00	0.00	0.09	0.18	0.27	0.27	0.50	0.21	0.26	0.29	0.27	0.25	0.22
C. rhizophorae	Cupped oyster	0.37	0.36	0.35	0.21	0.15	0.20	0.03	0.28	0.29	0.28	0.18	0.00	0.00	0.00	0.09	0.18	0.27	0.27	0.50	0.23	0.29	0.31	0.29	0.28	0.24
Holothuria scabra	Sea cucumber	0.27	0.26	0.25	0.11	***0.05***	0.10	0.23	0.97	1.00	0.98	***0.69***	0.13	0.09	0.09	0.27	0.45	***0.64***	0.64	0.10	0.17	0.36	0.41	0.41	***0.37***	0.24

Overall climate risk was also found to be fairly low for red snapper and pompano, as well as for sobaity and goldlined sea breams, typically held in cage culture (Table 10). Each of these Indo-Pacific species are within or close to their thermal tolerance ranges in Omani waters and at little thermal risk. Typically held in cage culture, their risk to flooding or storm surge is also less than for shore-based culture (albeit not absent); there is moreover limited evidence for disease risk for these species. Our estimate for overall climate risk is higher for gilthead sea bream, which relates to this species' temperature affinities which are lower than typical seawater temperatures in Oman, implying a high thermal risk; this has, however, not halted its successful cultivation in Oman where it is the most widely cultivated sea bream species – but other risk factors (flooding risk, disease risk) are lower in this species. How different components of risk may differently affect the overall climate risk is exemplified by the northernmost governorate of Musandam where thermal risk to gilthead seabream is highest, but where there is low risk from flooding or storm surge and from low-oxygen levels. Hence these low scores contribute to a lower overall climate risk for aquaculture in Musandam than in other governorates.

Omani abalone and sea cucumber aquaculture are characterised as low risk, partly due to these species being within natural temperature ranges in Omani waters, especially off the governorates of Dhofar and Al Wusta, respectively, where these species would be cultivated.

For aquaculture of Atlantic salmon in Oman, a fully controlled and isolated RAS system are proposed, which would render production of salmon relatively independent from ambient temperature or other environmental conditions; this does, however, necessitate fully temperature controlled systems given salmon's cold-water preferences. This would also make the risk from pathogen introduction low, provided original stock is safely sourced free of OIE listed diseases, and then where possible raised from local brood-stock.

In combination, the framework of climate risk assessment for aquaculture species in Oman, as presented here and summarised in Table 10, allows for a rapid screening of the key components of risk that may impact each species in each governorate. It also allows for clear communication of four key components of risk to a wider audience including stakeholders. Identifying four major components of risk to the sector – thermal sensitivity, exposure to flooding and storm surge, hazard from low-oxygen, and vulnerability to disease, and enable prioritisation of adaptation measures aimed at reducing or eliminating risk.

The risk metrics presented here should not be seen as 'final risk scores'; they will evolve with increasing scientific knowledge for aquaculture species, particular for diseases where new pathogens may emerge or be discovered. By and large, we hope that this climate risk assessment for Omani aquaculture may facilitate successful dialogue with stakeholders that could contribute to strengthened climate resilience in the sector.

9 Discussion

A strength of the fisheries analysis performed here is that the results of the fleet and wilayat CRAs can be directly compared. It is interesting to note that there is a fine balance between each of the components (S, E, V, and H) such that a fishing fleet or wilayat can attain a high risk score overall so long as it amasses relatively moderate scores across the board for each of the four constituents. Notably, some wilayats scored high because of perceived socio-economic vulnerabilities and a lack of adaptive capacity, whereas others attained an almost identical risk score but primarily because of biological sensitivities [S] or a lack of species diversity in catches [E]. Because of the differing reasons that particular fleets or wilayats scored higher or lower (the only Wilyat that scored consistently high across all four constituent metrics was Ja'alan Banī Bū Ḥassan), industry and government should respond in different ways to face the challenges and risks associated with climate change.

In some cases, such as in Al-Khābūrah wilayat, strengthening the resilience of local regions and communities would be of most benefit such as by creating alternative employment opportunities. In other regions, fleet risks dominate (e.g. Al-Jāzer and Ad-Duqm), and therefore increasing the efficiency and diversity of the fleet would appear to be a priority. Some areas, such as Ja'alan Banī Bū Ḥassan appear to require both types of intervention, and therefore present the greatest adaptation challenges. There is, no "one-size-fits-all" solution that can be applied across all 49 fleets or 30 coastal wilayats or even, in some cases, across a country: climate adaptation plans need to be tailored to these realities.

Climate risk and vulnerability analyses have a key role to play in shaping the development of fishery or aquaculture development plans. By increasing awareness of the elements that contribute most to a fleet or region's risk, CVAs and CRAs can help prioritise adaptation actions to mitigate this risk and thereby maximise the effectiveness of limited resources. Lavoie et al. (2018) revealed that on the whole, high-level indices derived as part of a CVA were indicative of real vulnerability in fishing communities, but that several important factors affecting community vulnerability were not being reflected in the quantitative indices and may prove very difficult to adequately quantify in the future. Taking the outputs of the CRA reported here, we suggest that government and development agencies should work with the most vulnerable fishing communities identified in Oman to enhance resilience and to build adaptive capacity (AC). For example, Cinner et al. (2018) synthesized research across a range of disciplines to highlight how AC in the fisheries sector can be reinforced across five key domains. These are: (i) the assets that people can draw upon in times of need; (ii) the flexibility to change strategies; (iii) the ability to organize and act collectively; (iv) learning to recognize and respond to change; and (v) the agency to determine whether to change or not.

Improved governance can drive actions to reduce the vulnerability of fleets and regions. Investments and support for developing new, or switching between, fishing, storage, transport and processing technologies can increase the efficiency of fleet operations and, therefore, enhance resilience. Increasing regional development, including the provision of employment opportunities outside the fisheries sector, reduces regional vulnerability (Allison et al. 2009; Badjeck et al. 2010). Regional, national and local governments have a role to play in adapting fisheries and ocean-dependent regions to the risks presented by climate change.

In carrying out a Climate Vulnerability Assessment (CVA) or a Climate Risk Assessment (CRA), researchers are faced with many methodological choices and subjective decisions that can greatly impact the final rankings. Monnereau et al. (2017) highlighted sources of bias in previous vulnerability assessments of Small Island Developing States. These authors noted several shortcomings that have relevance here, namely that: (1) many authors have not correctly scaled socio-economic indicators to take account of large differences in human population size (i.e. in communities or countries), (2) that many authors have used too few indicators, raising concerns about the sensitivity of the results to the inclusion or exclusion of any particular indicator; and (3) that authors have failed to account for potential redundancy among indicators, which might lead to a disproportionate effect on the final vulnerability or risk scores. In the present analysis we have tried to account for the different sizes of the wilayats by either dividing quantities by the total population size in each (e.g. monthly income per capita) or by the kilometres of coastline in each wilayat (e.g. tonnes of fish landed; value of fish landed; number of fishing vessels, number of fishermen). It is true that for some elements of the CRA, very little information was available, with which to construct metrics and this was especially so with regard to socioeconomic vulnerability [V] in the fleet-based analysis (revenue per crew member). Ideally, we would have had access to a wider range of economic information on fleets (such as net profit margin), but even so we feel that the 'vulnerability' dataset used did adequately capture the most important driver of 'vulnerability', and that it was appropriately weighted. We acknowledge that there is some redundancy in having multiple indicators of 'fisheries reliance' (×4) or 'adaptive capacity' (×3) in the wilayat-based analysis and that these were largely correlated (see discussion above), but we have corrected for this using a nested approach, whereby we calculate component indices for F and AC that are only afterwards combined to yield an overall metric for 'socioeconomic vulnerability' [V].

Monnereau et al. (2017) opted to rank-transform all indicators, which is a different approach to that taken by Allison et al. (2009) where 'raw' values were used. We adopted rank-transformation here for the level of cyclone hazard and for 'Fisheries landings (value) per km coastline", where data were heavily skewed in real-terms. Monnereau et al. (2017) stated that rank-transforming each indicator should yield more robust results as this approach allows for standardizing data across indicators independently of the shape of the distribution of values underlying each indicator, while minimizing the influence of extreme values in a consistent manner. In realty, rank-transforming or using log-transformation made little real difference to the results obtained by Monnereau et al. (2017) and hence, in general, we have not transformed our datasets, except to normalize and re-scale each to range from 0 to 1 before combination.

Guides for the application of vulnerability assessments have been developed especially with reference to fisheries and aquaculture (FAO, 2015). Several reports on "best practice" have now been published (e.g. Johnson et al., 2016). Conclusions from this work are that diversification of approaches and methodologies has enabled new insights into the causes and consequences of vulnerability, but at the same time has also caused confusion among practitioners and led to the voicing of a need for greater clarification and guidance. A particularly challenging issue relates to whether or not 'weighting' should be applied when combining different components. The approach taken by Cinner et al. (2013) was to weight indicators based on expert opinion, i.e. it was assumed that some indicators may contribute more to adaptive capacity than others. By contrast, Allison et al. (2009) looked at various different weighting schemes and found the overall vulnerability ranking remained largely unchanged.

Our analysis argues that reef-associated fish species (snappers, grunts, groupers, lobsters etc.), by virtue of their habitat specificity, restricted distribution and life-history characteristics, are much more sensitive to climate change in comparison with open-water pelagic species (such as tunas and dolphinfish) which are highly migratory, have a global distribution and are demonstrably able to tolerate a much broader range of sea water temperatures. Unlike in temperate systems where warmer-water species can 'invade' from nearer the equator and where cold-preferring species can retreat poleward (see Cheung et al. 2009), systems in the tropics such as the seas around Oman are heavily constrained because they are already some of the warmest places on the planet and therefore few species are adapted to cope with even warmer temperatures. That being said, worldwide there are localities with warmer temperatures ('hot spots') than are currently experienced in Oman, including areas of the Arabian Gulf (Riegl et al., 2011) and some commercial fish species are able to persist quite happily in these regions (Feary et al. 2010). This bodes well for the future, where average sea surface temperatures around Oman could rise by 2-3°C over the next 50 or so years (see figure 3) as a result of anthropogenic climate change, although prospects may depend on what happens to the magnitude and timing coastal upwelling around Oman, as this currently helps to cool the region (especially on the Arabian Sea coast) allowing productive pelagic fisheries to persist.

In our analyses for fisheries we do not consider the potential impact of ocean acidification nor of declining oxygen levels (although the latter is considered in the aquaculture analysis). For free-living fish and invertebrate species it could be argued that sensitivity to these factors is inherently built into the species sensitivity metrics, given that more mobile species can re-distribute if they encounter adverse conditions whereas more sedentary, reef-associated species cannot, and hence they are already scored as being more sensitive. In addition, fish and invertebrates along the coast of Oman are subjected to very variable pH conditions yet they continue to persist. In the northern Arabian Sea, pH varies strongly throughout the year, depending on the season. In summer, monsoonal winds drive upwelling of CO_2 rich deep water all along the Omani coast. pH can drop to as low as 7.93, compared to 8.05–8.09 during winter months (Omer, 2010). Repeated measurements from survey cruises in the Arabian Sea reveal an overall decrease in average pH between 1960 and 2000. This decrease amounts to ~0.1 pH units in the upper 50 m and 0.2 pH units at 300 m depth (Piontkovski and Queste, 2016)

The CRA conducted for aquaculture in Oman is novel in that it is based on proposed aquaculture developments rather than existing in-situ establishments and production facilities. The government has articulated its ambition to greatly expand the aquaculture sector, most notably for shrimp, yet climatic concerns (temperature change and storm surge or inundation risk) could hamper this expansion unless appropriate adaptation and resilience building measures are implemented.

A screening-level risk assessment, such as the one carried out here provides guidance to scientists, resource managers and stakeholders on how climate change is expected to alter the physiology, life cycles and environment of aquaculture species and, ultimately, the way they are farmed. The study also highlights knowledge gaps in aquaculture research across a broad range of farming systems. Outcomes from this assessment will focus attention towards the research required to underpin more detailed quantitative assessments of higher risk industries and regions within Oman within the region and thus more optimal allocation of human and operational resources. Aquaculture production provides significant social and economic benefits globally, and the methods presented provide a broadly applicable, cost-effective and rapid approach to assessing risk and should be relevant to many other regions around the world.

10 References

Adger, W.N. (1999) Social vulnerability to climate change and extremes in coastal Vietnam. World Development 27 (2), 249-269.

AGEDI (2016a) Final Technical: Regional Desalination and Climate Change. LNRCCP. CCRG/IO. https://agedi.org/item/technical-report-regional-desalination-and-climate-change/

Al-Buloshi A, Al-Hatrushi S, Charabi Y (2014) GIS-based framework for the simulation of the impacts of sea level rise and coastal flooding in Oman. Journal of Earth Science & Climate Change 5: 238.

Al-Rashdi KM, Claereboudt MR, Eeckhaut I (2018) Preliminary trials on hatchery and larval development of the sea cucumber, *Holothuria scabra* (Jaeger 1883), in the Sultanate of Oman. Asian Journal of Fisheries and Aquactic Research 2 (3): 1-9.

Al-Rashdi KM, Ibrahim FS, Al-Habsi SH (2011) Aquaculture Research in the Sultanate of Oman. Ministry of Agriculture and Fisheries Wealth, Aquaculture Centre, Muscat, Sultanate of Oman. 44 pp.

Al-Rashdi KM, Iwao T (2008) Abalone, *Haliotis mariae* (Wood 1828), hatchery and seed production trials in Oman. Agricultural and Marine Sciences 13: 53-63.

Allison, E.H., Perry, A.L., Badjeck, M.-C., Adger, N.W., Brown, K., Conway, D., Halls, A.S., Pilling, G.M., Reynolds, J.D., Andrew, N.L., Dulvy, N.K. (2009) Vulnerability of national economies to the impacts of cli-mate change on fisheries. Fish and Fisheries 10(2): 173-196.

Anderson, C.N.K., Hsieh, C-H., Sandin, S.A., Hewitt, R., Hollowed, A., Beddington, J., May, R.M., Sugihara, G. (2008) Why fishing magnifies fluctuations in fish abundance. Nature 452: 835–39.

Barsley, W., De Young, C., Brugère, C. (2013) Vulnerability assessment methodologies: an annotated bibliography for climate change and the fisheries and aquaculture sector. FAO Fisheries and Aquaculture Circular No. 1083. Rome, FAO. 43 pp.

Bento, R., Hoey, A.S., Bauman, A.G., Feary, D.A. and Burt, J.A. (2016) The implications of recurrent disturbances within the world's hottest coral reef. Marine Pollution Bulletin, 105, 466-472. doi.org/10.1016/j.marpolbul.2015.10.006

Badjeck, M. C., Allison, E. H., Halls, A. S. & Dulvy, N. K. Impacts of climate variability and change on fishery-based livelihoods. Mar. Policy 34, 375–383 (2010).

Blasiak R, Spijkers J, Tokunaga K, Pittman J, Yagi N, O ¨sterblom H (2017) Climate change and marine fisheries: Least developed countries top global indexof vulnerability. PLoS ONE 12(6):e0179632.https://doi.org/10.1371/ journal.pone.0179632

Bopp, L., Resplandy, L., Orr, J.C., Doney, S.C., Dunne, J.P., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Séférian, R., Tjiputra, J. and Vichi, M. (2013) Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences, 10, 6225-6245.

Callaway R, Shinn AP, Grenfell SE, Bron JE, Burnell G, Cook EJ, Crumlish M, Culloty S, Davidson K, Ellis RP et al. (2012). Review of climate change impacts on marine aquaculture in the UK and Ireland. Aquat. Conserv. 22: 389–421.

Cardona, O.D., van Aalst, M.K., Birkmann, J., Fordham, M., McGregor, G., Perez, R., Pulwarty, R.S., Schipper, E.L.F., Sinh, B.T. (2012) Determinants of risk: exposure and vulnerability. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) eds C B Field et al (Cambridge, UK, and New York, NY, USA: Cambridge University Press) pp 65–108.

Carpenter, J. (1966) New measurements of oxygen solubility in pure and natural water. Limnology and Oceanography, 11, 264-277.

Cheung, W.W.L., Bruggeman, J., Butenschön, M. (2018) Chapter 4: Projected changes in global and national potential marine fisheries catch under climate change scenarios in the twenty-first century. In: Impacts of climate change on fisheries and aquaculture - Synthesis of current knowledge, adaptation and mitigation options. FA O Fisheries and Aquaculture Technical Paper No. 627. Rome, FAO. pp63-86. http://www.fao.org/3/i9705en/i9705en.pdf

Cheung, W.W.L., T.J. Pitcher and D. Pauly, 2005. A fuzzy logic expert system to estimate intrinsic extinction vulnerabilities of marine fishes to fishing. Biol. Conserv. 124:97-111.

Cheung WWL, Watson R, Pauly D (2013) Signature of ocean warming in global fisheries catch. Nature 497, 365-368.

Cinner, J. E., Adger, W. N., Allison, E. H., Barnes, M. L., Brown, K., Cohen, P. J., Gelcich, S. et al. 2018. Building adaptive capacity to climate change in tropical coastal communities. Nature Climate Change, 8: 117–123.

Cinner, J. E., Huchery, C., Darling, E.S., Humphries, A.T., Graham, N.A.J., Hicks, C.C., Marshall, N., McClanahan, T.R. (2013) Evaluating social and ecological vulnerability of coral reef fisheries to climate change. PLoS ONE 8: e74321.

Colburn, L., Jepson, M., Weng, C., Seara, T., Weiss, J., Hare, J.A. (2016) Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf Coasts of the United States (2016) Marine Policy. 74: 323-333.

Connelly, A., Carter, J., Handley, J. & Hincks, S. Enhancing the practical utility of risk assessments in climate change adaptation. Sustain. 10, 1–12 (2018).

Doubleday ZA, Clarke SM, Li X, Pecl GT, Ward TM, Battaglene S, Frusher S, Gibbs PJ, Hobday AJ, Hutchinson N, Jennings SM, Stoklosa R (2013) Assessing the risk of climate change to aquaculture: a case study from south-east Australia. Aquacult. Environ. Interact. 3: 163–175.

Ellis JR, Engelhard GH, Pinnegar JK (2010) Ecotypes. In: Rijnsdorp AD, Peck MA, Engelhard GH, Möllmann C, Pinnegar JK (eds) Resolving climate impacts on fish stocks. ICES Coop. Res. Rep. No. 301, pp 10-20, 301-367.

Engelhard GH, Ellis JR, Payne MR, ter Hofstede R, Pinnegar JK (2011) Ecotypes as a concept for exploring responses to climate change in fish assemblages. ICES J. Mar. Sci. 68: 580-591.

Evan, A.T., Camargo, S.J. (2011) A Climatology of Arabian Sea Cyclonic Storms. JOURNAL OF CLIMATE, 24:140-158. DOI: 10.1175/2010JCLI3611.1

FAO (2015) Assessing climate change vulnerability in fisheries and aquaculture: Available methodologies and their relevance for the sector, by Cecile Brugère and Cassandra De Young. FAO Fisheries and Aquaculture Technical Paper No. 597. Rome, Italy.

FAO (2018) Impacts of climate change on fisheries and aquaculture - Synthesis of current knowledge, adaptation and mitigation options. FA O Fisheries and Aquaculture Technical Paper No. 627. Rome, FAO. 628 pp. http://www.fao.org/3/i9705en/i9705en.pdf

Feary, D., Burt, J.A., Bauman, A., Usseglio, P., Sale, P.F. and Cavalcante, G. (2010) Fish communities on the world's warmest reefs: what can they tell us about impacts of a climate change future? Journal of Fish Biology, 77, 1931-1947.

Fordyce, A., Tracy, A., Scott, H. and William, L. (2019) Marine Heatwave Hotspots in Coral Reef Environments: Physical Drivers, Ecophysiological Outcomes, and Impact Upon Structural Complexity. Frontiers in Marine Science, 6, 498. doi: 10.3389/fmars.2019.00498.

Foster,K., Foster, G., Tourenq, C. and Shuriqi, M. (2011) Shifts in coral community structures following cyclone and red tide disturbances within the Sea of Oman (UAE). Marine Biology, 158, 955-968.

Fritz, H.M., Blount, C., Albusaidi, F.B., Al-Harthy, A.H.M. (2010) Cyclone Gonu Storm Surge in the Sea of Oman (2010) Y. Charabi (ed.), Indian Ocean Tropical Cyclones and Climate Change. Springer Science, DOI 10.1007/978-90-481-3109-9_30

FSD (2019) Fisheries Statistics Book 2019. General Directorate of Planning & Development, Fisheries Statistic Department. Sultanate of Oman. 244pp.

Jennings S, Stentiford GD, Leocadio AM, Jeffery KR, Metcalfe JD, Katsiadaki I, et al. (2016) Aquatic food security: insights into challenges and solutions from an analysis of interactions between fisheries, aquaculture, food safety, human health, fish and human welfare, economy and environment. Fish and Fisheries 17: 893–938.

Haggag, M. and Badry, H. (2012) Hydrometeorological Modelling Study of Tropical Cyclone Phet in the Arabian Sea in 2010. Atmospheric and Climate Sciences, 2, 174-190 dx.doi.org/10.4236/acs.2012.22018

Hare, J.A., Morrison, W.E., Nelson, M.W., Stachura, M.M., Teeters, E.J., Griffis, R.B., Alexander, M.A., Scott, J.D., Alade, L., Bell, R.J., Chute, A.S., Curti, K.L., Curtis, T.H., Griswold, C.A. (2016) A vulnerability assessment of fish and invertebrates to climate change on the Northeast UK continental shelf. PLoS ONE 11: e0146756.

Hassan, R. M., Scholes, R. & Ash, N. Ecosystems and Human Well-being - Current State and Trends: Findings of the Condition and Trends Working Group of the Millennium Ecosystem Assessment. Millenn. Ecosyst. Assess. Ser. (v. 1) xxi, 917 (2005). doi:10.1016/j.fm.2010.10.016

Helly, J.J. and Levin, L.A. (2004) Global distribution of naturally occurring marine hypoxia on continental margins. Deep Sea Research I, 51, 1159-1168. doi.org/10.1016/j.dsr.2004.03.009

Hereher, M., Al-Awadhi, T., Al-Hatrushi, S., Charabi, Y., Mansour, S., Al-Nasiri, N., Sherief, Y., El-Kenawy, A. (2020) Assessment of the coastal vulnerability to sea level rise: Sultanate of Oman. Environmental Earth Sciences (2020) 79:369. https://doi.org/10.1007/s12665-020-09113-0

Hoegh-Guldberg, O., Cai, R., Poloczanska, E., Brewer, P. G., Sundby, S., Hilmi, K., Fabry, V.J. and Jung, S. (2014) The Ocean. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1655-1731.

IPCC. (2001). Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the IPCC. http://www.grida.no/publications/other/ipcc_tar/www.grida.no/publications/other/ipcc_tar/

IPCC. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. (2019). doi:https://www.ipcc.ch/report/srocc/

Islam, S.N. and Winkel, J. (2017) Climate Change and Social Inequality. DESA Working Paper No. 152. ST/ESA/2017/DWP/152, UN Department of Economic & Social Affairs. www.un.org/esa/desa/papers/2017/wp152_2017.pdf

Johnson, J. E. et al. Assessing and reducing vulnerability to climate change: Moving from theory to practical decision-support. Mar. Policy 74, 220–229 (2016).

Kamermans P, Taylor NGH, Doyle TK, Ferreira JG, Cubillo AM, Kreiß C, Elliott M, Peck MA (2020) Climate change and the European aquculture sector. In: Peck MA, Catalán IA, Damalas D, Elliott M, Ferreira JG, Hamon KG, Kamermans P, Kay S, Kreiß CM, Pinnegar JK, Sailley SF, Taylor NGH (2020, eds) Climate Change and European Fisheries and Aquaculture: 'CERES' Project Synthesis Report, Hamburg, Germany. doi: 10.25592/uhhfdm.804.

Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P, Srivastava, A.K. and Sugi, A. (2010) Tropical cyclones and climate change. Nature Geoscience, 3, 157-163. doi.org/10.1038/ngeo779

Lavell, A., Oppenheimer, M., Diop, C., Hess, J., Lempert, R., Li, J., Muir-Wood, R., Myeong, S. (2012) Climate change: new dimensions in disaster risk, exposure, vulnerability, and resilience. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J.

Lavoie, A., Sparks, K., Kasperski, S., Himes-Cornell, A., Hoelting, K., and Maguire, C. 2018. Ground-truthing social vulnerability indices of Alaska fishing communities, Coastal Management, 46: 359–387.

Long, M.C., Deutsch, C. and Ito, T. (2016) Finding forced trends in oceanic oxygen. Global Biogeochemical Cycles, 30, 381-397.

MAFW (Ministry of Aquaculture and Fisheries Wealth) (2019) Fisheries Lab Outcomes: A Promising Economic Potential. Ministry of Agriculture and Fisheries, Sultanate of Oman, 57 pp.

Monnereau, I., Mahon, R., McConney, P., Nurse, L., Turner, R., & Vallès, H. (2017) The impact of methodological choices on the outcome of national-level climate change vulnerability assessments: An example from the global fisheries sector. Fish and Fisheries 18(4), 717–731.

MTC (2005) Appendix 7-2. Wilayat Characteristics - The Study on Road Network Development in the Sultanate of Oman. Final Report. March 2005. Ministry of Transport & Communications, Sultanate of Oman. 60pp.

Murakami, H., Sugi, M. and Kitoh, A. (2013) Future changes in tropical cyclone activity in the North Indian Ocean projected by high-resolution MRI-AGCMs. Climate Dynamics, 40, 1949. doi.org/10.1007/s00382-012-1407-z

Musick, J.A. (1999) Criteria to define extinction risk in marine fishes: The American Fisheries Society initiative. Fisheries, 24, 6 –14.

NCSI (2012) The Final Findings of the Household Expenditure and Income Survey (For the period 20 May 2010 - 19 May 2011). National Center for Statistics and Information (NCSI). Sultanate of Oman, Muscat. 32pp.

Noori, R., Tian, F., Berndtsson, R., Abbasi, R., Vesali Naseh, M.R., Modabberi, A., Soltani, A. and Klöve, B. (2019) Recent and future trends in sea surface temperature across the Persian Gulf and Sea of Oman. PLoS ONE 14(2):e0212790. doi.org/10.1371/ journal.pone.0212790

Omer, W.M.M. (2010) Ocean acidification in the Arabian Sea and the Red Sea - factors controlling pH. MSc Thesis, Faculty of Mathematics and Natural Sciences Geophysical Institute, University of Bergen, Norway. https://www.semanticscholar.org/paper/Ocean-acidification-in-the-Arabian-Sea-and-the-Red-Omer/66a16058bec6995e4440a350ed8b40a865fc5f72

Oppenheimer, M. et al. Emergent risks and key vulnerabilities. in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Field, C. 431 et al.) 1039–1099 (Cambridge University Press, 2014).

Ottersen, G., Hjermann. D.Ø., Stenseth. N.C. (2006) Changes in spawning stock structure strengthen the link between climate and recruitment in a heavily fished cod (Gadus morhua) stock. Fisheries Oceanography 15: 230–243.

Palenzuela, O., Redondo, M.J. and Cali, A. (2014) A new intranuclear microsporidium, *Enterospora nucleophila* n. sp., causing an emaciative syndrome in a piscine host (*Sparus aurata*), prompts the redescription of the family Enterocytozoonidae. International Journal for Parasitology 44, 189–203.

Pauly, D. and Kinne, O. (2010) Gasping fish and panting squids: oxygen, temperature and the growth of water-breathing animals (Vol. 22). Oldendorf/Luhe, Germany: International Ecology Institute.

Peeler E, Scott A (2018) Development of aquatic animal health legislation for Oman. UK-Gulf Marine Environment Partnership (UK-GMEP) Programme Report, Centre for Environment, Fisheries & Aquaculture Science (Cefas), Weymouth, UK. 20 pp.

Petitgas, P., Rijnsdorp, A.D., Dickey-Collas, M., Engelhard, G.H., Peck, M.A., Pinnegar, J.K., Drinkwater, K., Huret, M., Nash, R.D.M. (2013) Impacts of climate change on the complex life cycles of fish. Fisheries Oceanography 22: 122–139.

Phillips, B. & Pérez-Ramírez, M. Climate Change Impacts on Fisheries and Aquaculture: A Global Analysis. (John Wiley and Sons Inc., 2018).

Pinnegar, J.K., Engelhard, G.H., Norris, N.J., Theophille, D., Sebastien R.D. (2019) Assessing vulnerability and adaptive capacity of the fisheries sector in Dominica: long-term climate change and catastrophic hurricanes. ICES journal of Marine Science, Volume 76, Issue 5, 09-10 2019, Pages 1353–1367.

Piontkovski, S.A. and Al-Oufi, H.S. (2015) The Omani shelf hypoxia and the warming Arabian Sea. International Journal of Environmental Studies, 72, 256-264.

Piontkovski, S.A. and Claereboudt, M.R. (2012) Interannual changes of the Arabian Sea productivity. Marine Biology Research, 8, 189-194.

Piontkovski, S.A. and Queste, B.Y. (2016) Decadal changes of the Western Arabian sea ecosystem. International Aquatic Research, 8, 49-64.

Poloczanska, E. S. et al. Global imprint of climate change on marine life. Nat. Clim. Chang. 3, 919–925 (2013).

Prins T (2015) Towards a blue revolution in a hydrocarbon society. MSc Diss., Utrecht University, The Netherlands, 150 pp.

Rafiq, L., Blaschke, T. and Tajbar, S. (2015) Arabian Sea cyclone: Structure analysis using satellite data. Advances in Space Research, 56 (10), 2235-2247. doi.org/10.1016/j.asr.2015.07.039

Reynolds, M. (1993) Physical oceanography of the Gulf, Strait of Hormuz, and the Sea of Oman: Results from the Mt Mitchell expedition. Marine Pollution Bulletin, 27(1), 35-39.

Riegl, B.M., Purkis, S.J., Al-Cibahy, A.S., Abdel-Moati, M.A. and Hoegh-Guldberg, O. (2011) Present limits to heat-adaptability in corals and population-level responses to climate extremes. PLoS ONE, 6, e24802. doi.org/10.1371/journal.pone.0024802

Rijnsdorp, A. D., Peck, M. A., Engelhard, G. H., Möllmann, C., and Pinnegar, J. K. 2009. Resolving the effect of climate change on fish populations. ICES Journal of Marine Science, 66: 1570–1583.

ROPME (2013) State of the Marine Environment Report- 2013. ROPME/GC-16 /1-ii Regional Organization for the Protection of the Marine Environment, Kuwait, 225 pp.

Sadrinasab, M. and Jochen, K. (2004) Three-dimensional flushing times of the Persian Gulf. Geophysical Research Letters, 312(24). doi: 10.1029/2004GL020425.

Shepherd, S.A., Al-wahaibi, D. and Al-Azri , A.R. (1995) Shell Growth Checks and Growth of the Omani Abalone Haliotis mariae. Marine & Freshwater Research, 46, 575-82.

Shirvani, A., Nazemosadat, S.M.J. and Kahya, E. (2015) Analyses of the Persian Gulf sea surface temperature: prediction and detection of climate change signals. Arabian Journal of Geosciences, 8: 2121-2130. doi 10.1007/s12517-014-1278-1

Stentiford, G.D., Neil, D.M., Peeler, E.J., Small, H.J., Flegel, T.W., Vlak, J.M., Jones, B., Morado, F., Moss, S., Lotz, J., Bartholomay, L., Behringer, D.C., Hauton, C., and Lightner, D.V. (2012) Disease will limit future food supply from the global crustacean fishery and aquaculture sectors. Journal of Invertebrate Pathology 110, 141–157.

Stramma, L., Schmidtko, S., Levin, L.A. and Johnson, G.C. (2010) Ocean oxygen minima expansions and their biological impacts. Deep Sea Research Part I: Oceanographic Research Papers, 57, 587-595. doi.org/10.1016/j.dsr.2010.01.005

Strømme, T. (1986) The Pelagic and Demersal Fish Resources of Oman. -Results of the R/V Dr. Fridtjof Nansen Surveys in Oman 1983 - 1984. Final Report, Institute of Marine Research, Bergen, Norway. December 1986. 103pp.

Turner, B.L., Kasperson, R.E., Matsone, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A. (2003) A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences of the United States of America 100, 8074–8079.

UNEP (1994) Implications of climate change in the ROPME region: An overview. UNEP Regional Seas Reports and Studies Number 155. United Nations Environment Programme (UNEP), 25 pp.

Vaquer-Sunyer, R. and Duarte, C.M. (2011) Temperature effects on oxygen thresholds for hypoxia in marine benthic organisms. Global Change Biology, 17: 1788-1797. doi:10.1111/j.1365-2486.2010.02343.x

Wabnitz, C.C.C., Lam, V.W.Y., Reygondeau, G., Teh, L.C.L, Al-Abdulrazzak, D., Khalfallah, M., Pauly, D., Palomares, M.L.D., Zeller., D. and Cheung, W.W.L. (2018) Climate change impacts on marine biodiversity, fisheries and society in the Arabian Gulf. PLoS ONE, 13: e0194537. doi.org/10.1371/journal.pone.0194537

11 Appendices

Appendix Table 1. Individual characteristics (temperature tolerance, habitat specificity and vulnerability to fishing) for 150 commercially important fish and shellfish species in Oman.

Species	Fishbase Name	LANDING CATEGORY	Average Landings (tonnes)	Maximum preferred temperature (TP90, °C)	Horizontal habitat preference	Vertical habitat preference	Mobility	Vulnerability	%	SPECIES SENSITIVITY
Plectorhinchus playfairi	Whitebarred rubberlip	Sweetlips	205.00	28.05	Reef-associated	Demersal	Sedentary	High	58	4.0
Epinephelus radiatus	Oblique-banded grouper	Grouper	65.25	28.93	Reef-associated	Demersal	Sedentary	High	61	3.7
Plectorhinchus schotaf	Minstrel sweetlips	Sweetlips	670.75	28.95	Reef-associated	Demersal	Sedentary	High	57	3.7
Trichiurus lepturus	Largehead cutlassfish (Ribbonfish)	Ribbonfish	12829.00	28.48	Coastal	Benthopelagic	Mobile	High	57	3.3
Plectorhinchus flavomaculatus	Lemon sweetlips	Sweetlips	341.75	27.92	Reef-associated	Demersal	Mobile	Moderate to High	47	3.3
Trachinotus africanus	Southern pompano	Large Jacks	68.50	27.63	Reef-associated	Benthopelagic	Mobile	Moderate to High	47	3.3
Argyrops filamentosus	Soldierbream (sparid)	Seabream	934.00	28.45	Reef-associated	Demersal	Mobile	Moderate	40	3.3
Scyllarides squammosus	Blunt slipper lobster	Lobster	4.00	27.52	Reef-associated	Demersal	Sedentary	Low to Moderate	30	3.3
Scarus arabicus	Arabian parrotfish	Other demersal	2328.25	28.45	Reef-associated	Demersal	Sedentary	Low to Moderate	29	3.3
Sphyraena barracuda	Great barracuda	Baracuda	2326.00	28.91	Reef-associated	Pelagic	Mobile	Very High	79	3.3
Carangoides fulvoguttatus	Yellowspotted trevally	Large Jacks	1029.50	28.81	Reef-associated	Pelagic	Mobile	High to Very High	66	3.3
Lutjanus malabaricus	Malabar blood snapper	Snapper	93.00	28.84	Reef-associated	Demersal	Mobile	High	60	3.3
Epinephelus tukula	Potato grouper	Grouper	157.25	29.04	Reef-associated	Demersal	Sedentary	High to Very High	66	3.3
Epinephelus tauvina	Greasy grouper	Grouper	179.50	29.15	Reef-associated	Demersal	Sedentary	High	59	3.3
Sphyrna lewini	Scalloped hammerhead shark	Sharks	1458.00	28.14	Oceanic	Benthopelagic	Highly migratory	Very High	81	3.0

Makaira indica	Black marlin	Sailfish	139.25	28.38	Oceanic	Epipelagic	Highly migratory	Very High	78	3.0
Alopias pelagicus	Pelagic thresher	Sharks	288.25	28.57	Oceanic	Epipelagic	Highly migratory	High to Very High	73	3.0
Xiphias gladius	Swordfish	Sailfish	355.25	28.02	Oceanic	Epipelagic	Highly migratory	High to Very High	72	3.0
Istiophorus platypterus	Indo-Pacific sailfish	Sailfish	470.75	28.60	Oceanic	Epipelagic	Highly migratory	High to Very High	68	3.0
Pomatomus saltatrix	Bluefish	Other Large Pelagics	1215.00	27.44	Oceanic	Epipelagic	Highly migratory	High	63	3.0
Seriola dumerilii	Greater amberjack	Large Jacks	1363.00	28.23	Shelf	Pelagic	Mobile	Moderate to High	54	3.0
Rhinobatos punctifer	Spotted guitarfish	Rays	84.00	28.20	Shelf	Bathydemersal	Mobile	Moderate to High	52	3.0
Elagatis bipinnulata	Rainbow runner	Large Jacks	100.75	28.05	Shelf	Pelagic	Mobile	Moderate to High	51	3.0
Atractoscion aequidens	Geelbeck croaker	Croaker	2764.50	27.89	Coastal	Benthopelagic	Mobile	Moderate to High	51	3.0
Carcharhinus macloti	Hardnose shark	Sharks	948.25	28.70	Shelf	Benthopelagic	Mobile	Moderate to High	47	3.0
Loxodon macrorhinus	Sliteye shark	Sharks	468.00	28.65	Shelf	Benthopelagic	Mobile	Moderate to High	46	3.0
Pseudotolithus senegalensis	Cassava croaker	Croaker	2117.75	27.89	Coastal	Demersal	Mobile	Moderate	42	3.0
Mugil cephalus	Flathead grey mullet	Mullets	692.50	27.83	Coastal	Benthopelagic	Mobile	Moderate	42	3.0
Trachinotus botla	Largespotted dart	Large Jacks	3.75	28.70	Coastal	Benthopelagic	Mobile	Moderate	40	3.0
Ablennes hians	Flat needlefish	Needlefish	1096.25	28.62	Coastal	Pelagic	Mobile	Moderate	40	3.0
Pomadasys commersonnii	Smallspotted grunter	Sweetlips	828.00	27.63	Reef-associated	Demersal	Mobile	Low to Moderate	34	3.0
Haliotis mariae	Oman abalone	Abalone	39.50	27.50	Reef-associated	Demersal	Sedentary	Low	15	3.0
Caranx ignobilis	Giant trevally	Large Jacks	1598.50	28.96	Coastal	Pelagic	Mobile	Very High	82	3.0
Hemipristis elongata	Snaggletooth shark	Sharks	38.25	28.87	Shelf	Benthopelagic	Mobile	High to Very High	73	3.0
Carcharhinus limbatus	Blacktip shark	Sharks	786.25	28.87	Shelf	Benthopelagic	Mobile	High	55	3.0
Cheimerius nufar	Santer seabream	Seabream	3026.25	28.96	Reef-associated	Demersal	Mobile	Moderate	48	3.0
Carangoides gymnostethu	Bludger	Large Jacks	223.50	28.87	Reef-associated	Pelagic	Mobile	Moderate to High	47	3.0
Lethrinus nebulosus	Spangled emperor	Emperor	1969.00	28.81	Reef-associated	Demersal	Mobile	Moderate to High	46	3.0
Sphyraena jello	Pickhandle barracuda	Baracuda	4729.25	29.04	Reef-associated	Pelagic	Mobile	Very High	75	3.0
Lethrinus mahsena	Sky emperor	Emperor	153.25	29.10	Reef-associated	Demersal	Mobile	High	65	3.0

Alectis indica	Indian threadfish	Large Jacks	331.25	29.13	Reef-associated	Pelagic	Mobile	High	62	3.0
Thunnus albacares	Yellowfin tuna	Yellowfin tuna	26323.50	28.34	Oceanic	Epipelagic	Highly migratory	Moderate to High	51	2.7
Acanthocybium solandri	Wahoo	Kingfish	39.25	27.96	Oceanic	Epipelagic	Highly migratory	Moderate to High	46	2.7
Coryphaena hippurus	Dolphinfish	Other Large Pelagics	5044.50	27.96	Oceanic	Epipelagic	Highly migratory	Moderate	40	2.7
Acanthopagrus arabicus	Arabian yellowfin seabream	Seabream	97.25	28.42	Coastal	Benthopelagic	Mobile	Moderate	39	2.7
Rhabdosargus sarba	Goldstriped seabream	Seabream	232.25	28.43	Coastal	Demersal	Mobile	Moderate	36	2.7
Umbrina ronchus	Fusta drum	Croaker	172.25	27.86	Coastal	Demersal	Mobile	Moderate	36	2.7
Scomber japonicus	Chub mackerel	Other Small Pelagics	963.50	27.48	Shelf	Pelagic	Mobile	Low to Moderate	34	2.7
Carangoides equula	Whitefin trevally	Large Jacks	2.00	28.44	Shelf	Benthopelagic	Mobile	Low to Moderate	32	2.7
Arius tenuispinis	Thinspine sea catfish	Catfish	10286.50	28.45	Coastal	Demersal	Mobile	Low to Moderate	29	2.7
Epinephelus diacanthus	Spinycheek grouper	Grouper	625.50	28.70	Coastal	Demersal	Mobile	Low to Moderate	27	2.7
Siganus sutor	Shoemaker spinefoot	Rabbitfish	8.50	28.13	Coastal	Demersal	Mobile	Low to Moderate	26	2.7
Aetobatis narinari	Whitespotted eagle ray	Rays	47.00	28.85	Shelf	Benthopelagic	Highly Mobile	High to Very High	74	2.7
Caranx lugubris	Black jack	Large Jacks	38.75	28.89	Oceanic	Benthopelagic	Highly migratory	High	60	2.7
Pseudorhombus arsius	Largetooth flounder	Other demersal	41.50	28.98	Coastal	Demersal	Mobile	Moderate to High	49	2.7
Caranx sexfasciatus	Bigeye trevally	Large Jacks	1237.50	28.85	Coastal	Benthopelagic	Mobile	Moderate to High	45	2.7
Rachycentron canadum	Cobia	Cobia	214.50	28.77	Shelf	Pelagic	Mobile	Moderate	44	2.7
Carangoides chrysophrys	Longnose Jack	Large Jacks	268.00	28.84	Coastal	Pelagic	Mobile	Moderate	41	2.7
Parupeneus heptacanthus	Cinnabar goatfish	Other demersal	531.00	28.87	Reef-associated	Demersal	Mobile	Moderate	38	2.7
Himantura uarnak	Honeycomb stingray	Rays	117.25	29.00	Coastal	Benthopelagic	Mobile	Very High	90	2.7
Chanos chanos	Milkfish	Other Large Pelagics	598.50	29.00	Coastal	Benthopelagic	Mobile	Very High	76	2.7
Trachinotus blochii	Snubnose pompano	Large Jacks	331.25	29.12	Coastal	Benthopelagic	Mobile	High	63	2.7
Carcharhinus amblyrhyncoides	Graceful shark	Sharks	1550.25	29.10	Coastal	Epipelagic	Mobile	High	63	2.7
Chirocentrus dorab	Dorab wolf-herring	Other Large Pelagics	119.25	29.08	Coastal	Pelagic	Mobile	High	61	2.7

Lethrinus microdon	Smalltooth emperor	Emperor	1335.50	29.11	Reef-associated	Demersal	Mobile	Moderate to High	46	2.7
Caranx heberi	Blacktip trevally	Large Jacks	2271.00	29.10	Reef-associated	Pelagic	Mobile	Moderate to High	45	2.7
Sphyraena forsteri	Bigeye barracuda	Baracuda	431.25	29.15	Reef-associated	Pelagic	Mobile	Moderate	44	2.7
Epinephelus areolatus	Areolate grouper	Grouper	593.75	29.12	Reef-associated	Demersal	Sedentary	Moderate	36	2.7
Plectorhinchus pictus	Trout Sweetlips	Sweetlips	68.25	29.21	Reef-associated	Demersal	Sedentary	Moderate to High	52	2.7
Lutjanus rivulatus	Blubberlip snapper	Snapper	9.00	29.24	Reef-associated	Demersal	Sedentary	Moderate	42	2.7
Katsuwonus pelamis	Skipjack tuna	Skipjack	144.75	28.32	Oceanic	Epipelagic	Highly migratory	Moderate	38	2.3
Auxis thazard	Frigate tuna	Frigate tuna	1391.75	28.70	Oceanic	Epipelagic	Highly migratory	Low to Moderate	28	2.3
Scomberomorus commerson	Spanish mackerel (Kingfish)	Kingfish	3716.75	28.87	Oceanic	Epipelagic	Highly migratory	Moderate to High	52	2.3
Argyrops spinifer	King soldierbream (sparid)	Seabream	2434.25	28.77	Coastal	Demersal	Mobile	Moderate	39	2.3
Selar crumenophtalmus	Bigeye scad	Small Jacks	3426.00	28.76	Shelf	Pelagic	Mobile	Moderate	39	2.3
Saurida tumbil	Greater lizardfish	Other demersal	1244.50	28.85	Coastal	Demersal	Mobile	Moderate	38	2.3
Seriolina nigrofasciata	Blackbanded trevally	Large Jacks	14.75	28.79	Shelf	Benthopelagic	Mobile	Moderate	38	2.3
Sepia pharaonis	Pharaoh cuttlefish	Cuttlefish	9800.25	28.84	Coastal	Benthopelagic	Mobile	Low to Moderate	33	2.3
Trachurus indicus	Arabian scad (horse mackerel)	Other Small Pelagics	9624.00	28.85	Shelf	Pelagic	Mobile	Low to Moderate	31	2.3
Parastromateus niger	Black pomfret	Small Jacks	464.00	28.92	Coastal	Pelagic	Mobile	Low to Moderate	30	2.3
Psettodes erumei	Indian halibut	Other demersal	418.50	28.92	Coastal	Demersal	Mobile	Low to Moderate	29	2.3
Nemipterus bipunctatus	Delagoa threadfin bream	Other demersal	473.25	28.92	Coastal	Demersal	Mobile	Low to Moderate	28	2.3
Carangoides malabaricus	Malabar Jack	Large Jacks	1048.50	28.85	Reef-associated	Pelagic	Mobile	Low	25	2.3
Mulloidichthys vanicolensis	Yellowfin goatfish	Other demersal	208.50	28.99	Reef-associated	Demersal	Mobile	Low	23	2.3
Planiliza subviridis	Greenback mullet	Mullets	427.25	29.12	Coastal	Benthopelagic	Mobile	Moderate to High	53	2.3
Sarda orientalis	Striped bonito	Striped bonitto	2381.00	29.13	Coastal	Epipelagic	Highly migratory	Moderate to High	50	2.3
Protonibea diacanthus	Blackspotted croaker	Croaker	34.50	29.12	Coastal	Benthopelagic	Mobile	Moderate	45	2.3
Plotosus lineatus	Striped eel catfish	Catfish	6.50	29.11	Reef-associated	Demersal	Mobile	Low to Moderate	28	2.3

Caesio varilineata	Variable-lined fusilier	Other demersal	388.25	29.10	Reef-associated	Pelagic	Mobile	Low to Moderate	28	2.3
Sargocentron rubrum	Redcoat squirrelfish	Other demersal	7.75	29.09	Reef-associated	Demersal	Sedentary	Low	17	2.3
Chaetodon melapterus	Arabian butterflyfish	Other demersal	0.75	29.10	Reef-associated	Demersal	Sedentary	Low	11	2.3
Scomberoides commersonnianus	Talang queenfish	Queenfish	3919.00	29.18	Coastal	Pelagic	Mobile	High	64	2.3
Caranx melampygus	Bluefin trevally	Large Jacks	82.75	29.19	Coastal	Pelagic	Mobile	High	56	2.3
Parupeneus barberinus	Dash-and-dot goatfish	Other demersal	93.00	29.25	Reef-associated	Demersal	Mobile	Moderate	40	2.3
Parupeneus cyclostomus	Gold-saddle goatfish	Other demersal	31.50	29.25	Reef-associated	Demersal	Sedentary	Moderate	37	2.3
Epinephelus stoliczkae	Epaulet grouper	Grouper	46.75	29.21	Reef-associated	Demersal	Sedentary	Moderate	35	2.3
Lutjanus coeruleolineatus	Blueline snapper	Snapper	1084.00	29.80	Reef-associated	Demersal	Sedentary	Low to Moderate	32	2.3
Panulirus versicolor	Painted spiny lobster	Lobster	10.50	29.39	Reef-associated	Demersal	Sedentary	Low to Moderate	30	2.3
Lutjanus madras	Indian snapper	Snapper	490.50	29.25	Reef-associated	Demersal	Sedentary	Low to Moderate	27	2.3
Lutjanus bengalensis	Bengal snapper	Snapper	361.50	29.17	Reef-associated	Demersal	Sedentary	Low to Moderate	27	2.3
Siganus canaliculatus	Pearlspotted rabbitfish	Rabbitfish	2119.25	28.98	Coastal	Demersal	Mobile	Low	18	2.0
Sardinella longiceps	Indian oil sardine	Sardine	164928.25	28.71	Shelf	Pelagic	Mobile	Low	17	2.0
Sardinella gibbosa	Goldstripe sardinella	Sardine	1842.75	28.85	Coastal	Pelagic	Mobile	Low	16	2.0
Upeneus sulphureus	Sulphur goatfish	Other demersal	1.75	28.83	Coastal	Demersal	Mobile	Low	15	2.0
Selaroides leptolepis	Yellowstripe scad	Small Jacks	2763.75	28.88	Coastal	Pelagic	Mobile	Low	13	2.0
Sepia prashadi	Hooded cuttlefish	Cuttlefish	1846.50	28.78	Coastal	Benthopelagic	Mobile	Low	10	2.0
Thunnus tonggol	Longtail tuna	Longtail tuna	16673.50	29.16	Oceanic	Epipelagic	Highly migratory	Moderate to High	47	2.0
Pristipomoides filamentosus	Crimson jobfish	Snapper	562.50	29.11	Slope	Benthopelagic	Mobile	Moderate	43	2.0
Pristipomoides multidens	Goldbanded jobfish	Snapper	355.75	29.11	Slope	Bathydemersal	Mobile	Moderate	43	2.0
Gnathanodon speciosus	Golden trevally	Large Jacks	242.25	29.13	Shelf	Benthopelagic	Mobile	Moderate	38	2.0
Otolithes ruber	Tigertooth croaker	Croaker	1010.00	29.12	Coastal	Benthopelagic	Mobile	Moderate	37	2.0
Megalaspis cordyla	Torpedo scad	Small Jacks	974.50	29.13	Shelf	Pelagic	Mobile	Low to Moderate	29	2.0

Nemipterus zysron	Slender threadfin bream	Other demersal	522.75	29.13	Coastal	Demersal	Mobile	Low to Moderate	26	2.0
Alepes djedaba	Shrimp scad	Small Jacks	300.50	29.15	Reef-associated	Benthopelagic	Mobile	Low	25	2.0
Lethrinus lentjan	Pink ear emperor	Emperor	7266.75	29.10	Reef-associated	Demersal	Mobile	Low	25	2.0
Penaeus semisulcatus	Green tiger prawn	Shrimp	556.75	29.02	Coastal	Demersal	Sedentary	Low	15	2.0
Iago omanensis	Bigeye houndshark	Sharks	37.75	29.36	Shelf	Bathydemersal	Mobile	High	51	2.0
Gymnura poecilura	Long-tailed butterfly ray	Rays	414.00	29.24	Coastal	Benthopelagic	Mobile	Moderate to High	51	2.0
Cynoglossus bilineatus	Fourlined tonguesole	Other demersal	458.75	29.21	Coastal	Demersal	Mobile	Moderate to High	45	2.0
Platax orbicularis	Orbicular batfish	Other demersal	30.75	29.17	Coastal	Demersal	Mobile	Moderate	45	2.0
Chaenogaleus macrostoma	Hooktooth shark	Sharks	71.00	29.18	Shelf	Benthopelagic	Mobile	Moderate	42	2.0
Crenimugil seheli	Bluespot mullet	Mullets	2502.00	29.21	Coastal	Benthopelagic	Mobile	Moderate	40	2.0
Mulloidichthys flavolineatus	Yellowstripe goatfish	Other demersal	206.00	29.20	Reef-associated	Demersal	Mobile	Moderate	39	2.0
Scomberoides tala	Barred queenfish	Queenfish	443.25	29.25	Reef-associated	Pelagic	Mobile	Moderate	38	2.0
Epinephelus chlorostigma	Brownspotted grouper	Grouper	317.75	29.19	Reef-associated	Demersal	Mobile	Moderate	38	2.0
Acanthopagrus bifasciatus	Twobar seabream	Seabream	104.25	29.17	Reef-associated	Demersal	Mobile	Moderate	37	2.0
Carangoides armatus	Longfin trevally	Large Jacks	450.00	29.17	Reef-associated	Pelagic	Mobile	Moderate	35	2.0
Acanthurus sohal	Sohal surgeonfish	Other demersal	37.25	29.72	Reef-associated	Demersal	Mobile	Low to Moderate	33	2.0
Parupeneus macronemus	Long-barbel goatfish	Other demersal	75.50	29.20	Reef-associated	Demersal	Mobile	Low to Moderate	33	2.0
Carangoides bajad	Orangespotted trevally	Large Jacks	298.00	29.48	Reef-associated	Pelagic	Mobile	Low to Moderate	27	2.0
Lethrinus harak	Thumbprint emperor	Emperor	1368.75	29.32	Reef-associated	Demersal	Mobile	Low to Moderate	27	2.0
Panulirus homarus	Scalloped spiny lobster	Lobster	410.00	29.28	Reef-associated	Demersal	Sedentary	Low	21	2.0
Pristipomoides typus	Sharptooth jobfish	Snapper	686.25	29.12	Slope	Bathydemersal	Mobile	Moderate	39	1.7
Euthynnus affinis	Kawakawa	Kawakawa	7388.50	29.09	Oceanic	Epipelagic	Highly migratory	Moderate	37	1.7
Decapterus kurroides	Redtail scad	Small Jacks	5411.75	29.04	Shelf	Pelagic	Mobile	Low	25	1.7
Therapon theraps	Largescaled terapon	Other demersal	753.00	29.00	Coastal	Demersal	Mobile	Low	24	1.7

Rastrelliger kanagurta	Indian mackerel	Indian Mackerel	9688.25	29.02	Shelf	Pelagic	Mobile	Low	21	1.7
Sepioteuthis lessoniana	Bigfin reef squid	Other	194.00	29.12	Coastal	Benthopelagic	Mobile	Low	19	1.7
Atule mate	Yellowtail scad	Small Jacks	451.50	29.07	Coastal	Pelagic	Mobile	Low	19	1.7
Pomadasys argenteus	Bluecheek silver grunt	Sweetlips	463.00	29.32	Coastal	Demersal	Mobile	Moderate	38	1.7
Siganus javus	Streaked spinefoot	Rabbitfish	1259.25	29.24	Coastal	Demersal	Mobile	Low to Moderate	29	1.7
Nemipterus japonicus	Japanese threadfin bream	Other demersal	3.25	29.22	Coastal	Demersal	Mobile	Low to Moderate	26	1.7
Hemiramphus far	Black-barred halfbeak	Other Small Pelagics	155.00	29.19	Coastal	Epipelagic	Mobile	Low to Moderate	26	1.7
Lutjanus ehrenbergii	Blackspot snapper	Snapper	2556.75	29.57	Reef-associated	Demersal	Mobile	Low	19	1.7
Portunus segnis	Blue Swimmer Crab	Other	1412.00	29.81	Coastal	Demersal	Sedentary	Low	10	1.7
Amphioctopus aegina	Sand bird Octopus	Other	25.75	29.58	Coastal	Demersal	Sedentary	Low	10	1.7
Penaeus indicus	Indian white shrimp	Shrimp	209.00	29.18	Coastal	Demersal	Sedentary	Low	10	1.7
Encrasicholina punctifer	Buccaneer anchovy	Anchovy	11603.50	29.12	Oceanic	Epipelagic	Highly migratory	Low	12	1.3
Nematalosa nasus	Bloch's gizzard shad	Sardine	983.25	29.22	Coastal	Pelagic	Mobile	Low	23	1.3
Herklotsichthys quadrimaculatus	Bluestripe herring	Sardine	69.50	29.17	Coastal	Benthopelagic	Mobile	Low	15	1.3
Sardinella albella	White sardinella	Sardine	21339.00	29.21	Coastal	Pelagic	Mobile	Low	10	1.3

Centre for Environment Fisheries & Aquaculture Science

Cefas

About us

We are the Government's marine and freshwater science experts. We help keep our seas, oceans and rivers healthy and productive and our seafood safe and sustainable by providing data and advice to the UK Government and our overseas partners.

We are passionate about what we do because our work helps tackle the serious global problems of climate change, marine litter, over-fishing and pollution in support of the UK's commitments to a better future (for example the UN Sustainable Development Goals and Defra's 25 year Environment Plan).

We work in partnership with our colleagues in Defra and across UK government, and with international governments, business, maritime and fishing industry, non-governmental organisations, research institutes, universities, civil society and schools to collate and share knowledge.

Together we can understand and value our seas to secure a sustainable blue future for us all, and help create a greater place for living.

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Innovative, world-class science is central to our mission. Our scientists use a breadth of surveying, mapping and sampling technologies to collect and analyse data that are reliable and valuable. We use our state-of-the-art Research Vessel Cefas Endeavour, autonomous marine vehicles, remotely piloted aircraft and utilise satellites to monitor and assess the health of our waters.

In our laboratories in Lowestoft and Weymouth we:
- safeguard human and animal health
- enable food security
- support marine economies.

This is supported by monitoring risks and disease in water and seafood; using our data in advanced computer models to advise on how best to manage fish stocks and seafood farming; to reduce the environmental impact of man-made developments; and to respond to serious emergencies such as fish disease outbreaks, and to respond to oil or chemical spills, and radioactivity leaks.

Overseas, our scientists currently work in Commonwealth countries, United Kingdom Overseas Territories, South East Asia and the Middle East.

Our customer base and partnerships are broad, spanning Government, public and private sectors, academia, non-governmental organisations (NGOs), at home and internationally.

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